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AN INVESTIGATION OF THE NITRATE PROBLEM IN RUNNELS COUNTY, TEXAS

David C. Jones

Texas Water Development Board

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An Investigation of the Nitrate Problem in Runnels County, Texas

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AN INVESTIGATION OF THE NITRATE PROBLEM IN RUNNELS COUNTY, TEXAS

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ABSTRACT

This report describes the methods, results, conclusions, and recommendations of the investigation of the nitrate contamination in Runnels County, Texas. It was found that most water well contamination is due to naturally occurring nitrate. However, all the very high nitrate contamination problems (>1000 ppm) are principally due to nitrate from barnyards. The nitrate sources were confirmed utilizing the nitrogen isotope ratio technique. The nitrate contamination was caused by a rising water table which intersected and dissolved nitrate deposits from the soil. The rising water table was caused by a combination of low porosity aquifers, increased infiltration (decreased surface runoff) due to terracing, and several consecutive years of above normal rainfall. There appears to be no economical way to remove the nitrate from either the water or the soil. Recommendations for ways for the area residents to obtain potable water and for a continued monitoring program are included.

This report was submitted in fulfillment of Project Number 16060 HNI under the sponsorship of the Water Quality Office, Environmental Protection Agency.

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SECTION I

CONCLUSIONS

1. Most groundwater contamination problems are due to natural nitrate, i.e., nitrate whose occurrence cannot be attributed to activities of man.

2. The most probable source of this natural nitrate is degradation of vegetation.

3. The extensive oil exploration and production which have occurred in Runnels County did not contribute significantly to the nitrate problem.

4. The use of nitrogen fertilizers did not contribute significantly to the nitrate problem.

5. The present high nitrate concentrations in the groundwater were caused when a rising water table encountered and leached out nitrate from the soil.

6. The large rise in the water table was caused by low porosity of the aquifers, increased infiltration due to terracing, and by several consecutive years of above average precipitation.

7. Some nitrate contamination of the groundwater existed even before the recent rise in the water table.

8. The highest soil nitrate concentrations and the worst groundwater contamination occur in the vicinity of barnyards and septic tanks where nitrate from cattle or human wastes has been added to the natural nitrate.

9. In some cases, poor well construction has contributed to contamination of the groundwater by nitrate.

10. Not all of the soil nitrate has been leached out by the groundwater. Tremendous quantities still exist at depths less than 20 feet.

11. Additional nitrate will be leached if the water table rises again.

12. There is no reason to believe that the nitrogen which is presently added to the Runnels County soil each year exceeds that added in other areas.

13. The fact that soil nitrate is much higher under barnyards and under fields and pastures in Runnels County than in other areas indicates the environment is somehow conducive to the conversion of all available nitrogen to nitrate and conducive to the retention of that nitrate in the unsaturated soil zone.

14. The low porosity of the aquifers in Runnels County contributes to the high nitrate concentrations in the groundwater because little dilution can take place.

15. High soil nitrates probably exist in other areas in central and west Texas.

16. No indication of soil nitrate could be obtained from infrared photographs of trees and plants.

17. The nitrate problem in Runnels County is due to a combination of unfortunate circumstances:

a. Large quantities of natural nitrate are present in the soil.

b. The porosity of the aquifers is low.

c. Climatic conditions 20 years ago were such as to encourage terracing.

d. Climatic conditions changed to provide sufficient precipitation to drastically raise the water table, resulting in dissolution of part of the soil nitrate.

SECTION II

RECOMMENDATIONS

The most important parameter to be monitored in Runnels County is the water table. Much nitrate is still in the soil above the water table, and it will be leached out if the water table rises again. A rise in the water table could occur due to another period of unusually high rainfall. The only ways to prevent such a rise are extensive pumping of most of the wells in the county, or removal of terraces to increase runoff of rainwater. To aid in monitoring the water table in Runnels County it is recommended that another water level recorder be installed, preferably in the area between Wingate and Winters.

The change in water quality with time should be monitored in Runnels County to obtain information on how fast the aquifers "cleanse" themselves. The following wells are recommended for semiannual (summer and winter) or annual (summer) sampling for a complete water analysis: Wells 865, 309, 301, 386, 728, 105, 1004, and the Rowena City Well. If all of these wells cannot be checked, the first four are the most desirable. The eight wells listed above cover the spectrum of wells contaminated by natural nitrate, barnyard nitrate, septic tank nitrate, and virtually no nitrate.

It is recommended that soil nitrate studies be continued. This should include semiannual (winter and summer) determination of soil nitrate profiles at the sites of Hole 1 and Hole 12 and yearly isotope ratio determinations for wells 301, 309, 386 and 365. This information would reveal how soil nitrate moves with seasonal climatic changes and with the passages of time and reveal how stable the isotope ratio is with time. Information on the stability of the isotope ratio with time could be important in interpreting changes in nitrate contamination.

The nitrate problem in Runnels County should be a clear warning for other areas in West Texas. The problem was brought on by the presence of high nitrate levels in the soil and by a rising water table. If this problem is to be avoided in other areas, it is important to identify those areas which have high soil nitrate. Once located, water level recorders should be installed. Land management practices should be evaluated. If possible, nitrogen isotope ratios should be run to help identify sources of nitrate. If the water table starts rising into the danger zone, as many wells as possible should be extensively pumped and the water diverted to creeks or rivers. If the water table rise continues, a choice may be necessary between the soil conservation provided by terracing and the impaired groundwater quality also brought about by the terracing.

SECTION III

INTRODUCTION

Goals of This Study

This report describes the results of an investigation of the nitrate contamination of the groundwater in Runnels County, Texas. This program was jointly funded by the United States Environmental Protection Agency and the Texas Water Development Board.

This investigation had several goals, which are as follows:

1. To determine the extent and severity of the nitrate contamination of the groundwater
2. To collect data regarding the geology, hydrology, soil and water chemistry, and land use practices in the contaminated areas
3. To determine the source of the nitrate
4. To develop a photographic technique to detect areas of nitrate contamination
5. To recommend remedies for the contamination problem
6. To recommend an ongoing monitoring program for the contaminated areas.

To achieve the goals, three types of studies were undertaken:

1. A series of field studies consisting of collection and analysis of water and soil samples, geologic and hydrologic investigations, and collection of data on land use practices
2. A laboratory study in which a technique was devised to measure the nitrogen isotope ratio of the nitrogen in the nitrate from soil and water samples, the purpose being to determine the source of the nitrate.
3. A study of the near infrared reflectance of plants and trees grown in low and high nitrate areas, the purpose being to locate areas of nitrate contamination by aerial photography.

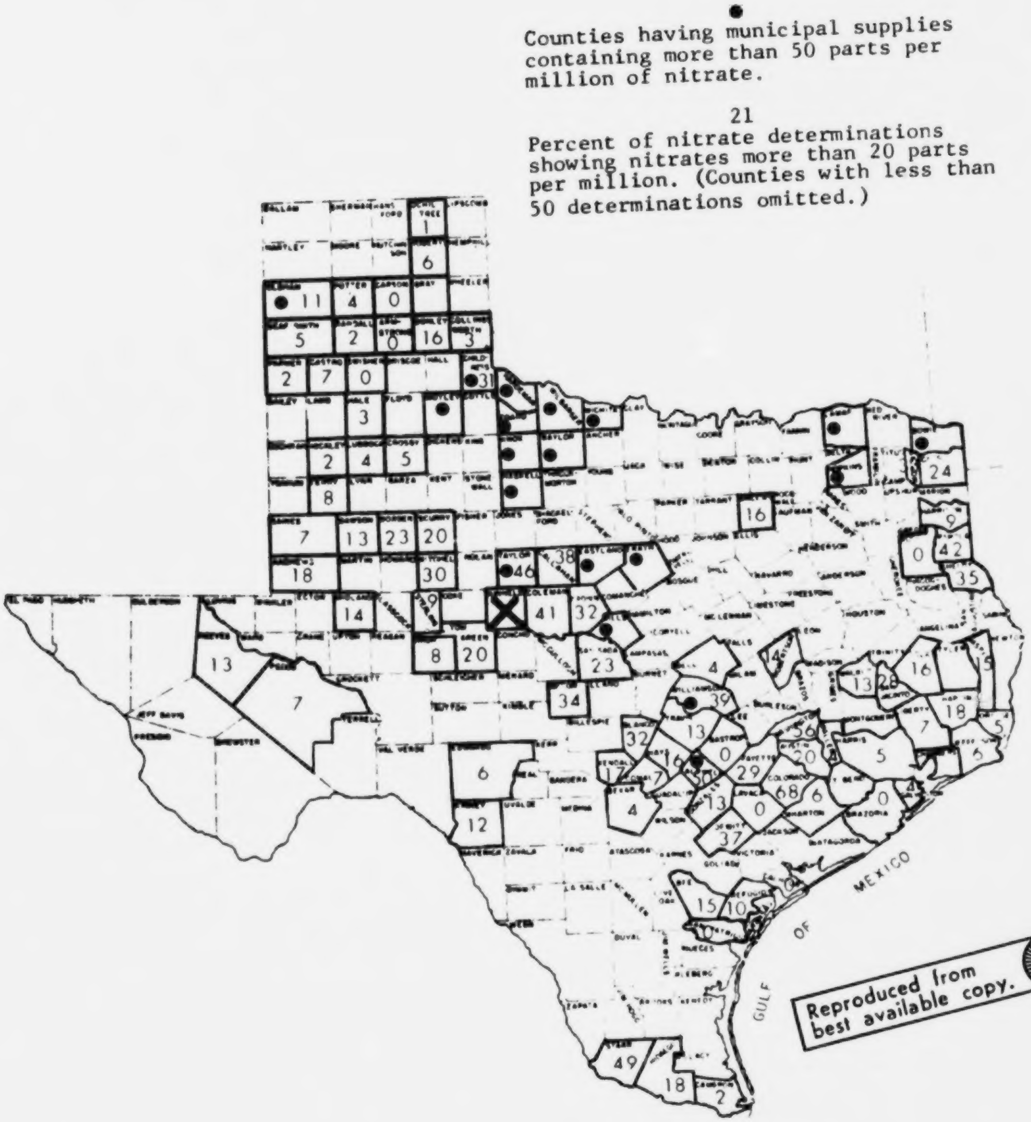
Nitrate in Other Areas of Texas

Runnels County appears to represent the worst case of what may be a widespread nitrate pollution problem in the groundwater aquifers of Texas. In 1951, George and Hastings[1] conducted a survey of some 20,000 water wells in 101 Texas counties. They arbitrarily assumed that any nitrate in excess of 20 ppm represented an unnaturally high nitrate concentration. On this basis they reported the percentage of the wells tested in a given county which had a nitrate level greater than 20 ppm. Their results are shown in Figure 1. Those counties with heavy borders were surveyed, and the number printed in the county represents the percentage of wells with a nitrate level greater than 20 ppm. A black dot indicates a municipal water supply with a nitrate level greater than 50 ppm. Runnels County, located in the west central part of the state, is marked by an X. Unfortunately, Runnels County was not included in George and Hastings' survey.

It can be seen that nitrate occurrence is widespread in Texas, and that the counties bordering Runnels County have a high percentage of nitrate-containing wells. It is noteworthy that the highest single nitrate sample (~1950 ppm) in the state came from Coleman County which adjoins Runnels County to the east. Some 3,000 of the 20,000 wells tested had greater than 20 ppm nitrate. George and Hastings noted that abnormal nitrate was found in water from formations of all geologic ages, in marine and non-marine formations, in limestone, sandstone, sand, gravel, and volcanics, in all climatic areas, in presence of and in absence of cultivation and pollution, and in wells of all depths. The authors could not suggest a reasonable source of the observed nitrate.

Health Effects of Nitrate

The best known problem due to nitrate consumption is methemoglobinemia, a cyanosis which is brought about by reduction of nitrate (NO_3^-) to nitrite (NO_2^-) by bacteria in the digestive tract, followed by absorption of the nitrite into the bloodstream where the nitrite oxidizes the ferrous ion (Fe^{++}) in hemoglobin to ferric ion (Fe^{+++}), thereby preventing the transport of oxygen by the hemoglobin. This results in a gradual suffocation (cyanosis). It is noteworthy that infants are most susceptible since the acidity of their stomach is considerably less than that of adults, resulting in a more favorable environment for the nitrate-reducing bacteria. The digestive system



● Counties having municipal supplies containing more than 50 parts per million of nitrate.

21 Percent of nitrate determinations showing nitrates more than 20 parts per million. (Counties with less than 50 determinations omitted.)

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Figure 1. Nitrate in Other Areas of Texas

of animals such as cattle (ruminants) also is conducive to this bacterial action. Therefore, when a nitrate problem occurs, it is first reflected in health problems of cattle or human infants.

It should be noted that the whole problem of methemoglobinemia is poorly understood. The nitrate or nitrite concentration at which methemoglobinemia becomes a problem may vary widely, and is most likely influenced by some as yet unidentified factor or factors. Because of the methemoglobinemia problem, the U. S. Public Health Service has set a recommended maximum limit of 45 ppm nitrate for potable water. It was observed in this study, however, that in a few cases both humans and animals were using water containing more than 1000 ppm nitrate with no apparent ill effects. In other areas, methemoglobinemia has resulted from using water with as little as 50 ppm nitrate. Clearly, more work is needed in the whole area of methemoglobinemia.

One point deserves further clarification. The high susceptibility of animals and human infants to methemoglobinemia derives from the bacteria in their digestive systems which can convert nitrate to nitrite. If the water which is being consumed already contains nitrite, however, even healthy adults will be susceptible. At least two mechanisms are available to provide nitrite in the drinking water. First, if the contamination is from surface pollution (e.g., barnyards or septic tanks) nitrite can be present due to incomplete oxidation of the nitrogenous waste materials. Second, nitrate in the groundwater can be reduced to nitrite by a chemical reaction with iron pipe or zinc coated (galvanized) pipe. This reaction consists of corrosion of the metal, with the nitrate acting as a hydrogen depolarizer.

Another important point is that water contaminated with nitrate cannot be purified by boiling. The nitrate concentration will instead be increased due to the loss of water by evaporation.

There is increasing evidence that nitrate and especially nitrite may be linked to cancer. It was shown by Lijinsky and Epstein that nitrite can react, under the conditions of temperature and acidity in the human stomach, with secondary amines (from cooked foods) to form nitrosamines, some types of which are highly carcinogenic.[2] Other studies also indicate a relationship between nitrate and cancer[3,4,5]. If such a relationship is proven, the Public Health Service limit of 45 ppm for nitrate in drinking water will have to be reevaluated. In addition, it may be even more important to set limits on nitrite in drinking water.

Clearly not all the effects of nitrate are yet known. It is claimed, however, that livestock may develop thyroid problems, rickets, enteritis, arthritis, and generally poor health from ingesting nitrates.[6]

Runnels County

Runnels County is located in west-central Texas and has an area of 1059 square miles. The climate of Runnels County is semi-arid, according to the Koeppen-Geiger classification.[7] The average rainfall is 22.6 inches. The average temperatures in January and July are 45.2° and 83.9°, respectively.

The economy of Runnels County is based on the production of cattle, sheep, hogs, cotton, wheat, sorghum, and oil. In 1970 there were 30,000 cattle, 66,000 sheep, and 3,600 hogs, on the farms and ranches. In addition, some 27,500 bales of cotton, 513,000 bushels of wheat, and 1,672,800 bushels of sorghum were harvested. Irrigated farming is minimal due to the lack of suitable water. Oil production was substantial during the 1950's (over 100 million barrels since 1927), but tapered off to only a few million barrels in 1970. The eastern and western sides of the county are mostly ranchland, whereas the central part of the country is largely devoted to farming. Even on the farms, however, some livestock raising is typical. The number of livestock raised on farms has decreased in the last few years because the farmers fear loss of the animals to nitrate poisoning.

Some open range ranching was being conducted in Runnels County by the late 1840's. By 1880 the population was 980, with ranching still the principal occupation. The central portion of the county was settled by farmers in the late 1890's. By 1930 the population had increased to 21,800, then slowly decreased to 12,100 by 1970. Except for the towns of Ballinger (population 4,200) and Winters (population 2,900), Runnels County residents normally rely on groundwater for their water supply. Since the advent of the nitrate problem, however, many residents have resorted to hauling water from Ballinger and Winters.

Rainfall is erratic in Runnels County as shown by Figure 2, which gives the yearly rainfall from 1910 to 1971. The early 1950's were a period of severe drought. The Colorado River dried up, as did the stock tanks and most

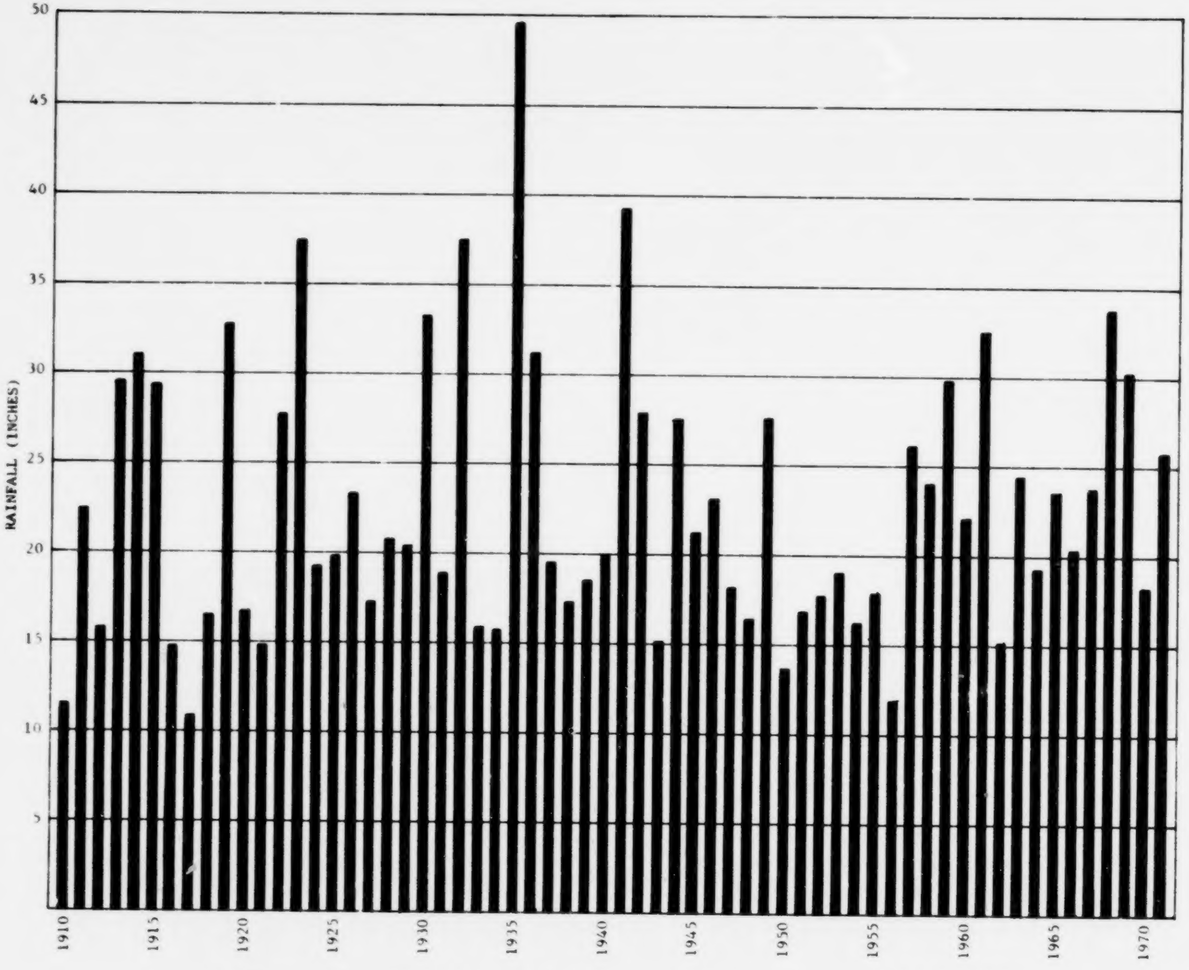

Figure 2. Rainfall in Runnels County, 1910-1971

of the water wells. This period was marked by extensive terracing of the farmland in an attempt to conserve all available precipitation and to prevent erosion of the topsoil.

Before this period an extensive network of creeks existed in Runnels County. These creeks provided numerous swimming and fishing holes year round. During the 1950's and 1960's, these creeks and their watersheds were leveled and terraced for maximum water conservation. By the late 1960's most of the creeks which originated in farming areas of the county had been eliminated because of the terracing across stream channels.

It should be noted that water quality problems are not new to Runnels County. Several investigations have been conducted regarding the high salinity of the groundwater in certain areas. Runnels County has been the site of considerable oil activity, with numerous holes being drilled for seismic exploration and oil production. Many of these holes penetrated the Coleman Junction formation, which contains highly saline water under a pressure sufficient to force it to the surface. Poor casing or plugging of some of these holes is at least partly responsible for the high salinity of some aquifers. Investigations of salinity problems were conducted by the Texas Board of Water Engineers in 1959[9], and the Texas Railroad Commission in 1968.[10] These investigations indicated the salinity was partly due to contamination and partly naturally occurring. No problems with high nitrate were reported.

The summers of 1968 and 1969 were marked by numerous cattle deaths in Runnels County. An investigation by the Texas Water Quality Board confirmed that the cattle deaths were due to nitrate poisoning.[11] The cattle deaths in 1969 prompted the Texas Water Development Board to conduct a more extensive investigation of the problem.[12] In this study, concentrated in the southwest part of the county, 20 of 23 wells were found to contain high nitrate levels. During this same period, the County Agent for Runnels County, Mr. C. T. Parker, advised all the farmers and ranchers to bring in samples of their well water. Approximately 850 of these water samples from throughout the country were analyzed for nitrate and total dissolved solids by the Texas A&M Extension Lab in Lubbock. Approximately 85% of these exceeded the Public Health Service limit of 45 ppm nitrate.

1967, 1968 and 1969 were years of above normal rainfall in Runnels County. In almost all of the farming areas of the county abnormally high water levels were observed in wells, with some wells becoming free-flowing. Many seeps developed, most in areas where no seeps had ever before been observed. The close timing between the rise in the water table and the onset of the nitrate problem was apparent, and led to two popular theories among the local residents. The first was that unplugged oil wells were permitting nitrate-laden water to be forced up from a deeper formation (e.g., Coleman Junction Formation), and the second was that fertilizer-contaminated water from the irrigated farming areas of the high plains had somehow filtered down into Runnels County. The possibility that the rising water had encountered and leached out nitrate deposits was also suggested.

Nitrogen Isotope Ratio Studies

Isotope Abundance

One of the goals of this study was to determine the source of the nitrate by studying its nitrogen isotope ratio. The nitrate anion (NO_3^-) contains one nitrogen atom and three oxygen atoms. There are two naturally occurring, stable (non-radioactive) isotopes of nitrogen, N^{14} and N^{15}. The nucleus of a N^{14} atom contains seven protons and seven neutrons, while the nucleus of a N^{15} atom contains seven protons and eight neutrons. The nitrogen gas in air is composed of 99.632% N^{14} and 0.368% N^{15}, i.e., 3680 of every million nitrogen atoms in air are N^{15}. Junk and Svec analyzed air samples from many localities and found no significant variation in the isotope composition of nitrogen.[26] In other nitrogen-containing compounds the N^{15} occurrence may be different from that in air, however.

The N^{15} content of any particular nitrogen species is expressed in terms of the nitrogen isotope ratio (δ), defined as follows:

$$\delta = \frac{N^{15}/N^{14}\ (\text{sample}) - N^{15}/N^{14}\ (\text{air})}{N^{15}/N^{14}\ (\text{air})} \times 1000$$

It can be seen that the nitrogen isotope ratio of air is used as a reference. For species with a higher N^{15} content than air the δ value will be positive, while species with a lower N^{15} content than air will have a negative δ value. Some isotope ratios which have been determined for various nitrogen containing species are shown in Table 1. An isotope ratio mass spectrometer will permit determination of δ values with an accuracy of ±0.5.

Mechanisms of Isotope Fractionation

It is worthwhile to consider why variations occur in the isotope ratios of different species. Because of the extra neutron in the N^{15} atom, it has a mass approximately 7% greater than a N^{14} atom. This greater mass causes N^{15} to behave in a slightly different manner from N^{14}. This different behavior may occur in several ways. Basically these consist of physical fractionation, chemical equilibrium fractionation, and chemical kinetic fractionation.

Physical fractionation can occur through diffusion, evaporation, and sublimation. In diffusion the lighter isotope (N^{14}) should have a higher velocity. In evaporation and sublimation the lighter isotope should have a higher vapor pressure. Since ammonia is sometimes an intermediate in the formation of nitrate, the evaporation of ammonia could be an important isotope fractionation mechanism in Runnels County.

Chemical equilibria fractionation (isotopic exchange equilibria) is the concentration of an isotope in one species of a chemical equilibria reaction. The values of the equilibrium constants are dependent on the different energy levels of the molecules involved. Urey[34] calculated the following isotopic equilibirum constants from partition functions:

	$T^\circ K$	Calculated α	Experimental
$N^{14}H_4^+ + \frac{1}{2}(N_2{}^{15}) \rightarrow N^{15}H_4^+ + \frac{1}{2}N_2{}^{14}$	298.1	1.023	not determined
$N^{14}H_4^+ + N^{15}H_3 \rightarrow N^{15}H_4^+ + N^{14}H_3$	298.1	1.035	1.034 ± .002
$N^{14}H_4^+ + N^{15}O \rightarrow N^{14}O + N^{15}H_4^+$	298.1	1.038	not determined
$\frac{1}{2}(N_2{}^{14}) + N^{15}H_3 \rightarrow \frac{1}{2}(N_2{}^{15}) + N^{14}H_3$	298.1	1.012	not determined

α = isotope equilibrium constant

Chemical equilibria fractionation could be important if adsorption on soil particles occurs.

Chemical kinetic fractionation describes the tendency of the two isotopes to react at different rates when undergoing the same reaction. If all the reactants are not converted into products (because of side reactions or

Table 1

Nitrogen Isotope Ratios for Various Species

Sample	Origin	Difference in N^{15}/N^{14} ratio from standard (parts per 1000)
	Plant Protein	
Leaves, white clover	Local	-6.5
Leaves, dandelion	Local	-2.8
Leaves, cedar	Local	1.3
Leaves, American elm	Local	1.9
Oats	Unknown	6.2
	Animal Protein	
Egg, domestic chicken	Local	5.8
Clam flesh	Atlantic Ocean	7.3
Lamb flesh	Unknown	5.0
Milk	Local	5.1
	Peat and Coal	
Peat	Eire	1.9
Peat	Junius, N. Y.	-2.8
Lignite	Bowman, N. D.	-1.2
Bituminous Coal	Pittsburgh, Pa.	-0.9
Cannel	Cannel City, Ky.	1.6
Anthracite	Gunnison, Colo.	-1.2
Anthracite	Lehigh, Pa.	-1.4
	Oil and Gas Wells	
Plaisted No. 1	Marchand Formation, Okla.	-3.5
Fletcher No. 10	Marchand Formation, Okla.	-7.6
Bitt No. 1	Hart Formation, Okla.	-11.5
Natural Gas	Washington County, Ark.	-5.9
	Rocks and Minerals	
Granite	Chelmsford, Mass.	-0.2
Granite	Milford, Mass.	-0.9
Pitchblende	Great Bear Lake, Canada	-2.3
	Inorganic Nitrogen	
Chile nitratite	Tarapaca, Chile	-2.6
Sal ammoniac	Paracutin, Mexico	13.0

incomplete reactions) the nitrogen isotope ratio will differ for the reactants and products. The particular isotope ratio for the products will depend on (a) the initial isotope ratio of the reactants, and (b) the particular reaction which occurred. It should be noted that environmental parameters can affect isotope fractionation. For example, high temperatures (hundreds of degrees) tend to lessen the tendency of the two isotopes to react at different rates, thus less isotope fractionation would be expected at high temperatures. This is because the slight differences in energy levels (due to the slightly different masses of the nitrogen atoms) become less important as the total energy of the system is increased by the added heat (molecular motion). Bacterially-aided reactions are another example of environmental influence on isotope fractionation. Such reactions often exhibit significant fractionation.

The purpose of the nitrogen isotope ratio study in Runnels County was to take advantage of the dependence of the nitrogen isotope ratio of a particular compound (specifically nitrate) on the type of reaction (or series of reactions) which formed that compound. As an example, nitrate formed during the manufacture of fertilizer should go through a different series of reactions than nitrate formed from animal wastes, and should therefore exhibit a different nitrogen isotope ratio.

Nitrogen Reservoirs

Nitrogen reservoirs are the atmosphere, lithosphere, hydrosphere and terrestrial biosphere. The atmosphere is the major reservoir. Atmospheric nitrogen isotopic composition appears uniform throughout.[27] Ammonia and nitrate of terrestrial origin are present in minute concentrations.[28] Hoering[29] suggests from isotopic data that atmospheric nitrate originates from oxidation of ammonia, not from lightning.

In the lithosphere, nitrogen in at least trace amounts is found in nearly all rocks. The average in igneous rocks is remarkably constant at 5 ppm.[30] Nitrogen is cosmically one of the more abundant elements, but in igneous rocks it has been depleted (relative to cosmic abundances) by a factor of approximately $7.5 \times 10^{+7}$. The less nitrogen in an igneous rock, the more enriched it is in N^{15}, possibly because lighter nitrogen is lost (diffuses) more easily.[31] White and Yagoda[32] analyzed nitrogen occluded in radioactive minerals (pitchblende and uraninite). They found very large δ values ranging from +457 to +605.

The nitrogen content of some sedimentary rocks is as high as 116 ppm. Miyake and Wada[33] found ammonia and organic nitrogen to be the major nitrogen compounds in marine sediments.

The ocean is one category of the biosphere that participates in the nitrogen cycle. Nitrogen is introduced primarily by the solution of atmospheric nitrogen in sea water. Benson and Parker[35] found an average δN^{15} of +0.13 for sea water in the North Atlantic Ocean. They attribute this positive δ value to fractionation at the air water interface and possible denitritication. All organic N had positive δN^{15} values, with higher δ values in the more complicated organisms. The δN^{15} in phytoplankton and seaweed has an average value of +7, whereas δN^{15} for zooplankton and fish is +10 and +15, respectively.

Nitrate Formation in Runnels County

It would appear that the nitrogen reservoir which supplied the nitrogen for the nitrate in Runnels County must be the atmosphere. Sedimentary rocks in the Permian formations are another possibility; however, the fact that nitrogen in such rocks typically occurs as ammonia and organic nitrogen argues against this. These compounds must be oxidized to obtain nitrate, and it does not seem reasonable that these compounds would sit around for hundreds of millions of years and then suddenly (in geologic terms) be oxidized to nitrate. If on the other hand, they were oxidized to nitrate long ago, it seems improbable that such near-surface nitrate deposits would have survived the humid climates of the Pleistocene and early Holocene epochs.

Assuming the atmosphere to be the important reservoir, several reaction paths for the production of nitrate can be visualized. The most reasonable paths are shown in Figure 3. These include (a) nitrate due to fixation by free-living bacteria, (b) nitrate from fertilizer, (c) nitrate from decayed plants, (d) nitrate from legumes, (e) nitrate from animal wastes, and (f) nitrate from human wastes. Not all possible paths are shown, e.g., nitrate formed by lightning or photochemical reactions in the atmosphere. During the period since the area has been farmed, introduction of nitrate due to legumes (nitrate D) is unlikely. Previous to this time, however, leguminous plants could have existed.

An examination of Figure 3 shows that the overall reaction schemes can be very complex due to possible recycling of the nitrate. This is only true at depths within the root

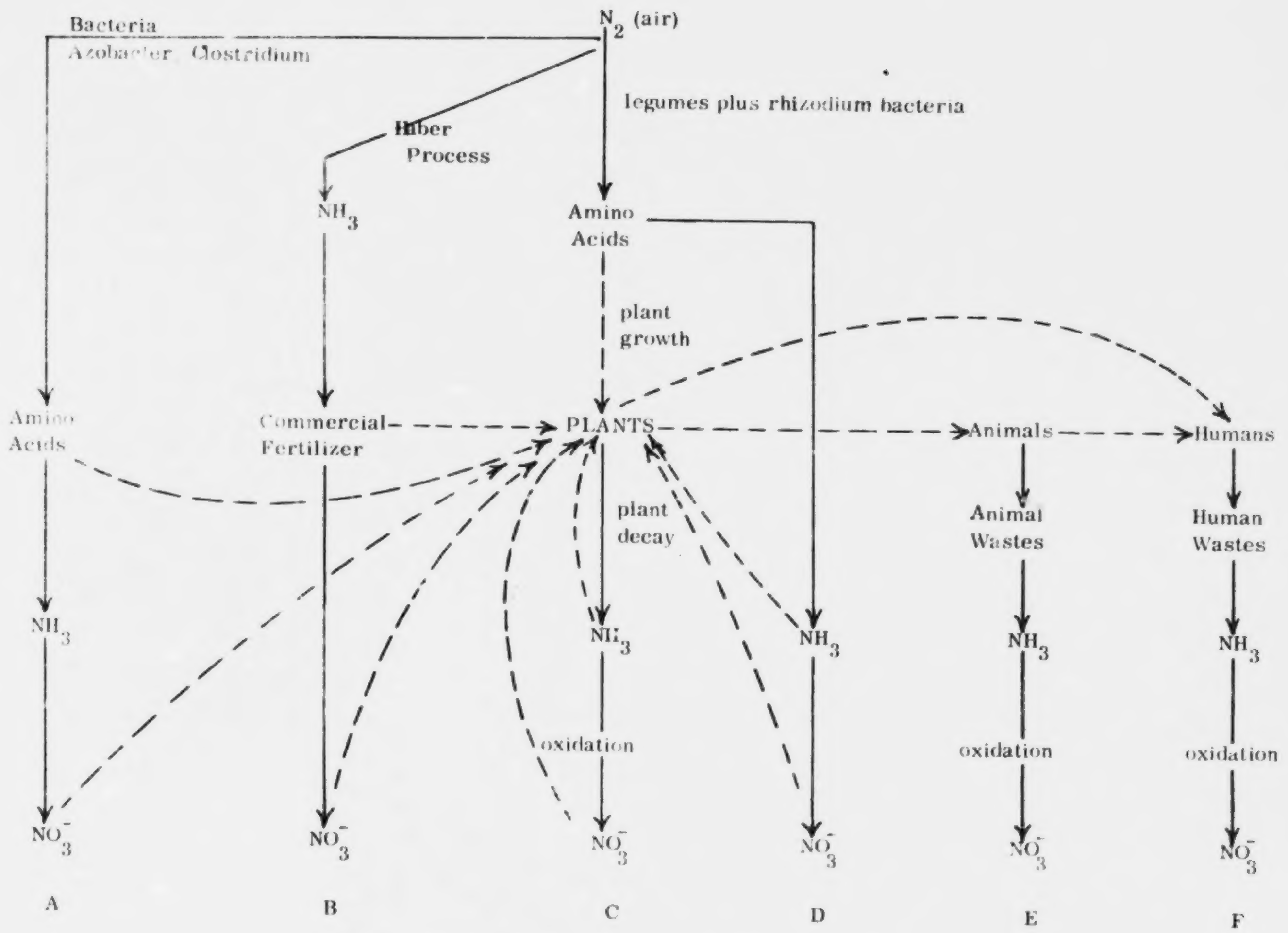
N2 (air)
Bacteria
Azobacter Clostridium
legumes plus rhizodium bacteria
Haber Process
NH3
Amino Acids
plant growth
Amino Acids
Commercial Fertilizer
PLANTS
Animals
Humans
plant decay
Animal Wastes
Human Wastes
NH3
NH3
NH3
NH3
NH3
oxidation
oxidation
oxidation
NO3-
NO3-
NO3-
NO3-
NO3-
NO3-
A
B
C
D
E
F

Figure 3. Mechanisms of Nitrate Formation

zone of plants, however. Once the nitrate is flushed beyond the root zone it should be unavailable for further recycling. It should be noted that many of the reactions shown are caused or aided by bacteria. It can be seen in Figure 3 that the ammonia and nitrate from human and animal wastes are not assumed to participate in recycling. This is because these wastes are concentrated at particular sites (barnyards or septic tanks) where plants either do not grow or are not numerous enough to consume significant amounts of the nitrate.

A complete examination of the nitrogen isotope behavior for all the reactions shown in Figure 3 was beyond the scope of this work. The approach used was to obtain nitrate samples from the soil at sites where the source of the nitrate could be reasonably predicted. The isotope ratio was determined for each of these "types" of nitrate, and compared to the isotope ratio which was determined for nitrate samples extracted from the groundwater at various sites in the county. In this way nitrate in the groundwater could be linked to a specific source through the nitrogen isotope ratio.

Infrared Photography Studies

The purpose of this study was to determine the feasibility of using infrared photography to detect near-surface nitrate deposits in the soil. Awareness of such potential trouble sites might in some cases permit prevention of the kind of problem which has occurred in Runnels County. For example, extensive pumping of many wells in the county in 1967, 1968 and 1969 might have prevented the rise in the water table and the subsequent leaching of the nitrate deposits. If successful, aerial infrared photographic surveys would provide an inexpensive method for detecting high nitrate areas.

The basic approach was to look for differences in the near infrared radiation reflected by normal plants and by plants exposed to large quantities of nitrate.

Background

The sun emits radiation over a broad range of wavelengths. The visible light given off by the sun cover the range of wavelengths (and colors) from 0.4 microns (violet) to 0.7 microns (red). Adjoining the visible spectrum on the upper end is the infrared region, which covers the range of wavelengths from 0.7 microns to 14 microns. That portion of the infrared spectrum from 0.7 to 1.35 microns is known as the "near infrared".

It has been found that considerable information can be obtained about the health of plants by studying the near infrared radiation (from the sun) which is reflected by the plant leaves. This study of reflected infrared radiation should not be confused with infrared imagery, in which infrared radiation emitted by the plant itself (wavelength 3 to 14 microns) is detected. Near infrared reflectance studies are done in bright sunlight. Infrared imagery studies are typically done at night. Both types of studies can provide useful information for agricultural, geological, and hydrological studies.

When radiation encounters some medium, one or more of three processes will take place. First, the radiation may be reflected. Second, the radiation may be absorbed. Third, the radiation may be transmitted on through the medium. If the radiation is in the near infrared region, and the medium is a plant leaf, all three processes take place to some extent, but most of the radiation is either reflected or transmitted. Transmitted radiation may subsequently be reflected if it strikes another leaf. This situation is shown in Figure 4. Note that reflected radiation actually penetrates into the cell structure of the leaf before being reflected. Because of this, the leaf structure and content will influence the reflected radiation[20]. An evaluation of the reflected radiation (which is recorded as a photograph on infrared-sensitive film) can therefore provide information about the plant which was photographed.

Figure 5 shows typical reflection (by a leaf) of light in the visible and infrared regions as a function of wavelength. It can be seen that most visible light is absorbed, however, a reflection peak occurs at about 0.55 microns. It is this reflection which gives plants their green appearance. It can also be seen that most infrared light is reflected from a healthy plant. This difference in reflection of visible and infrared light was put to good use in World War II for camouflage detection. The camouflage could easily duplicate the absorption of visible light, but not the reflectance of infrared light. Aerial infrared photographs could thus pinpoint camouflaged areas.

The reflectance spectrum in Figure 5 shows healthy plant behavior. If a plant is diseased, the microscopic leaf structure will be different, thus the reflectance of the leaf will change. Extensive use has been made of this characteristic to locate plant diseases by aerial photography. The technique is very sensitive and frequently can detect diseased plants before any sign of disease is apparent to the eye. This permits early treatment and minimizes crop losses.

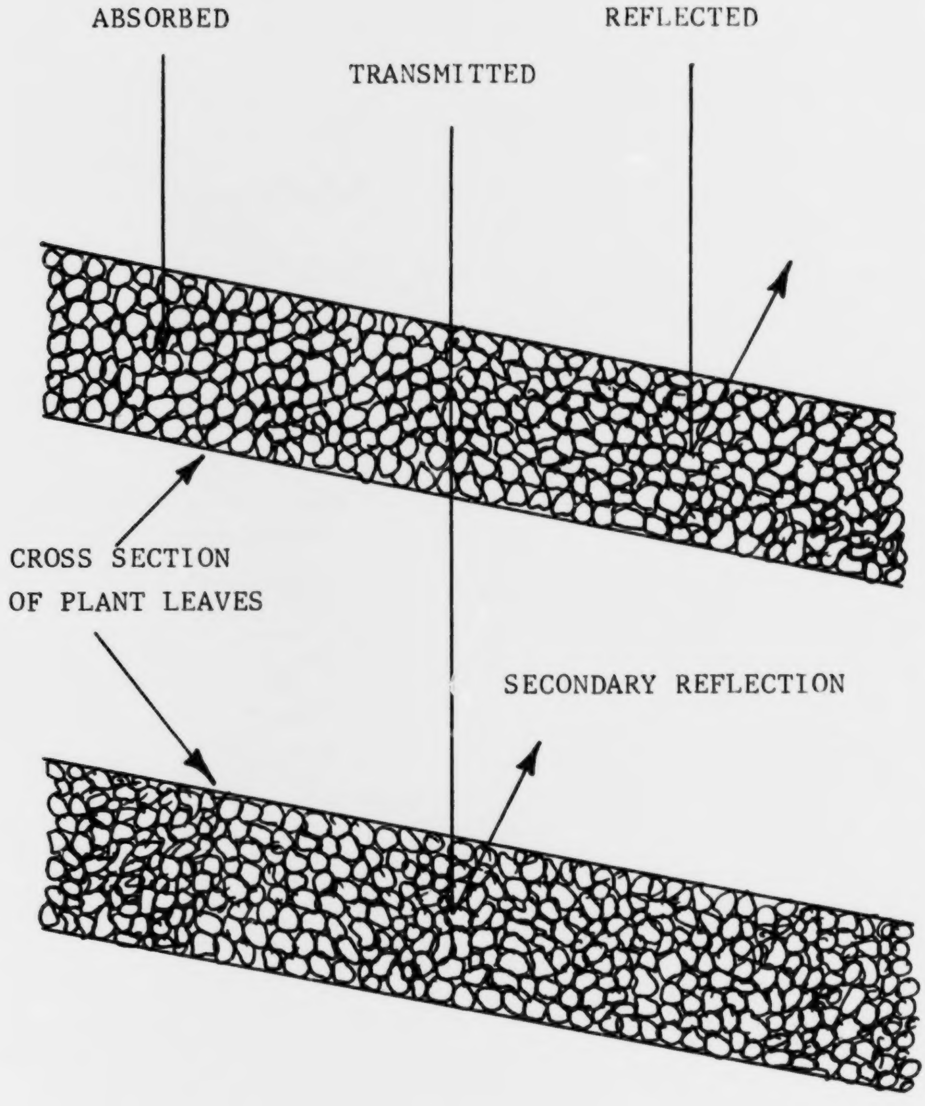
ABSORBED
TRANSMITTED
REFLECTED
CROSS SECTION
OF PLANT LEAVES
SECONDARY REFLECTION

Figure 4. Reflection of Infrared Light from a Leaf

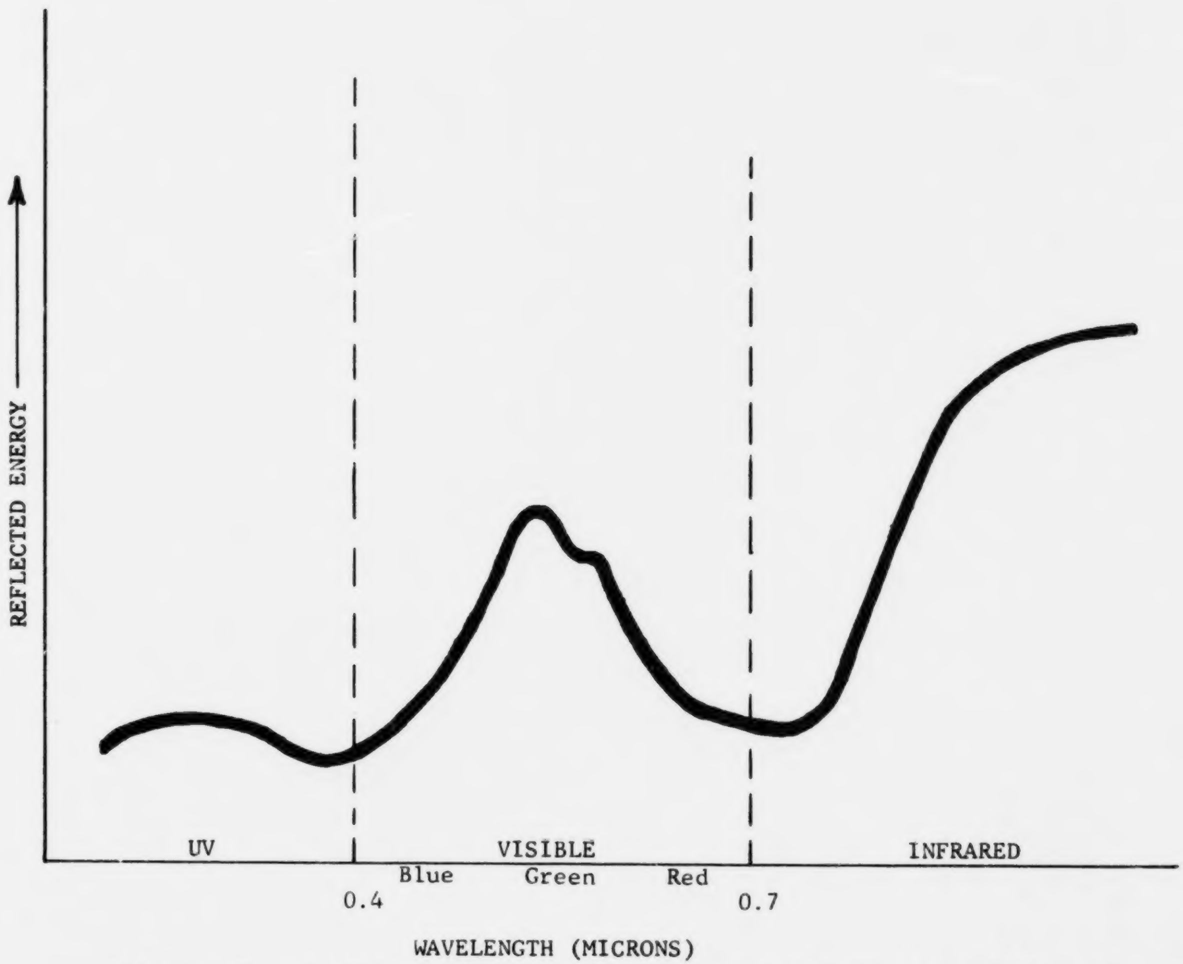

Figure 5. Reflection of Light from a Leaf as a Function of Wavelength

It was the goal of this study to determine whether exposure to high soil nitrate levels might cause a change in leaf structure which could be detected by studying photographs of infrared radiation reflected from the leaf.

It should be noted that no specific wavelength of infrared radiation is studied, but rather a range of wavelengths. This range depends on the type of film used in the camera and the type of filter used.

Just how excessive nitrate might affect plant leaf structure is not precisely known. The reflection of light from plant leaves depends on the morphology of the cell walls, intercellular air space, fluid within the cells, and the chloroplasts[40]. There is some indication that plants exposed to excess nitrate will store nitrate in the leaves until it is needed for conversion to plant protein[41]. This might cause a change in the reflected radiation. In addition, it has been observed[42,43] that high nitrates increase the chlorophyll content of leaf pigments. This also should change the reflected radiation.

It can be seen that the depth of the nitrate is important if plants are to be used as indicators of subsurface nitrate, i.e., the nitrate must not be below the root zone of the plant. The most ideal indicator for an area such as Runnels County would be the mesquite tree. The mesquite has a deep tap root and is widely occurring. Even heavily cultivated areas typically have a few mesquite trees along fence lines and around barnyards. Cultivated crops might be more sensitive to nitrate, however, their shallower root systems would not indicate deep nitrate deposits.

SECTION IV

EXPERIMENTAL METHODS

Data were collected in several types of studies. These included geological and hydrological studies, collection of information from local residents, studies of soil nitrate and water chemistry, studies of the nitrogen isotope ratio of the nitrate, and infrared photography studies of plants in the contaminated areas.

Survey of the Problem

This involved visiting many of the farms and ranches in Runnels County to collect water samples and obtain information. The area residents were very cooperative during this survey. In many cases the land had been passed down from father to son, so fairly lengthy historical data were available.

The water samples were collected in one quart plastic bottles, capped, and sent to the Texas Department of Health for analysis. The analysis was for nitrate, chloride, sulfate, fluoride, bicarbonate, sodium, calcium, silicate, magnesium, pH, and total dissolved solids. A few special analyses for nitrite, organic carbon (analyzed at a Department of Interior Laboratory), and orthophosphate were also performed. Whenever possible, the well being sampled was pumped for 15 minutes to assure that a representative sample of the groundwater was obtained. No preservation was added.

The information which was collected was of two types, well data and land use practices.

Well Data

a. Well location (on county map)

b. Well altitude (estimated from topographical maps)

c. Well depth

d. Depth to water

e. Age of well

f. Type of pump

g. Condition of casing

h. Distance, direction, and surface gradient to possible sources of contamination such as barnyards or septic tanks

Land Use Practices

a. Previous fertilizer usage in the area

b. History of livestock raising and confinement in the area

c. Terracing

d. Oil well exploration or production activities in the area

Geological and Hydrological Studies

Groundwater age dating was accomplished by determining tritium concentrations. Much of the groundwater exists in carbonate aquifers which would greatly complicate carbon dating. In addition, tritium age dating is a good technique for young water, especially if the tritium concentration in rainwater is known for the past several decades.

Continuous recordings of groundwater levels were maintained at two sites in the county by the Texas Water Development Board. These recorders were installed in July 1970.

Four aquifer tests were performed to determine storage coefficients and transmissivities. In these tests, one well was pumped at a known rate, and the water level in a nearby observation well was monitored as a function of time. Wells in both gravel and limestone aquifers were tested.

As a result of the extensive oil exploration in Runnels County, fairly complete geological data were available. This was supplemented by on site investigations of near-surface geology at selected sites in the county.

Soil Nitrate Studies

Eighty-four holes were drilled in Runnels County to investigate the nitrate content of the sub-surface soils. Four-inch diameter holes were drilled with an air-rotary drilling rig to a depth of 20 feet unless the water table was encountered first. Soil samples (in the form of finely divided particles) were collected every foot and stored in plastic bags.

The analytical procedure consisted of weighing out ¼ pound of the soil sample and leaching it with 500 ml of deionized water (with mixing) for 15 minutes. The solution-suspension was then tested for chloride and nitrate concentrations using Orion Research, Inc., specific-ion electrodes, model numbers 94-17A and 92-07, and the single-junction reference electrode, model number 90-01. These electrodes, and their reliability, were described by Manahan[15]. Chloride ion was found to interfere with nitrate at low nitrate concentrations. Consequently, all nitrate values are corrected for chloride interference. The clay and silt in suspension after mixing did not interfere with the electrode readings. For convenience, the nitrate values were converted to milligrams of nitrate per kilogram (mg/kg) of soil sample. Twenty random samples were checked by wet chemical analysis to determine the accuracy of the nitrate electrode. Analyses were generally within ten percent of the wet chemical analyses. Because of all the steps taken to determine the nitrate concentrations in the soils, a 20 percent error seems likely. Considering the number of samples analyzed and the difficulty of obtaining reproducible results in natural systems, plus the extremely high concentrations of nitrate, these experimental errors are acceptable.

There were basically four types of soils of interest — soil under barnyards, soil near septic tank laterals, soil in cultivated fields, and soil in pastures which had never been under cultivation. In most cases, the results of the groundwater analyses were used to select areas of interest for soil studies. In many cases, several holes were drilled in a particular area to try to determine the influence of a barnyard or septic tank on the subsurface nitrate of that area.

Nitrogen Isotope Ratio Determination

Isotope analysis is most conveniently performed on nitrogen gas (N_2). This means that all nitrate samples must be reduced to nitrogen gas, and this conversion must be performed without introducing any isotope fractionation during the sample preparation. Once the nitrate is converted to nitrogen gas, the gas must be purified to remove interfering species (e.g., carbon monoxide) and to remove species such as oxygen which might damage the filaments in the mass spectrometer. The techniques which were developed for sample collection and sample preparation were as follows.

Collection of Soil and Water Samples

Wells were pumped at least ten minutes before collection of water samples. (This step was found to be very important). Water samples were stored in one quart plastic bottles at room temperature. No effect was observed on the isotope ratio for storage times up to two months. The groundwater contained sufficient nitrate that concentration of the initial water sample was not required.

Soil samples were collected with an air-rotary drilling rig to a maximum depth of ten feet, a sample being collected every foot. Each sample was stored in a plastic bag. No difference was observed in isotope ratio between a sample which was kept frozen and one which was stored at room temperature for several days. This probably was because (a) the samples were well aerated during drilling thus preventing denitrification, and (b) the relatively brief period between collection and analysis did not permit significant conversion of organic nitrogen to nitrate. Weighed samples of soils were leached overnight in de-ionized water. The leachate was separated by centrifuging.

Preparation of Nitrogen Gas

Since only the isotope ratio of the nitrate was of interest, other oxidation states of nitrogen had to be removed. These included NH_4^+, organic nitrogen, and nitrite. (For groundwater samples this step was probably unnecessary due to the high nitrate concentration and low concentration of other species.)

a. The approximate nitrate concentration was determined using a specific ion electrode. An aliquot containing approximately 50 milligrams of nitrate was treated with 5 ml of sulfamic acid to convert any nitrite in the solution to nitrogen gas.

b. Following the technique of Bremmer and Keeney[3] for removing organic nitrogen and ammonia, the pH of the solution was raised to 10 by adding powdered magnesium oxide (MgO). This solution was steam distilled until 50 ml of distillate were collected. At this stage, interfering forms of nitrogen had been removed.

c. The outlet of the water-jacketed condenser was next immersed in a flask containing 50 ml of 0.1N HCl. Five mg of Devarda's alloy (50% passing 200 mesh screen, 100% passing 100 mesh screen) was added through a sidearm on the flask which was immediately re-stoppered. This solution was stirred for two hours without heating. The nitrate in the sample was reduced to ammonia during this stage.

d. The sample was next redistilled until 75 ml of distillate were collected in the 0.1 N HCl solution. Tests run on standards showed that 99+% of the nitrate in the original sample was converted to ammonia at this stage. (The distillation apparatus was later cleaned by distilling reagent grade ethanol until 50 ml of distillate were collected.)

e. The acidic ammonium solution was next titrated with 0.1 N NaOH to determine the amount of nitrate in the original sample. As soon as the end point was reached (at pH 5.3), the pH was immediately reduced to 2 by adding 10N HCl to prevent any evaporation of ammonia.

f. The sample was next concentrated by heating on a hot plate at 70-80°C until the volume was reduced to 5 to 10 ml. Standards revealed that no loss of ammonia occurred during this step.

g. A special apparatus is required from this stage on to prepare the sample. A diagram of this apparatus is shown in Figure 6. This apparatus basically consists of a sample reaction tube to react ammonia with hypobromite, a vacuum source, a pump for circulating the gas (Toeppler Pump), two furnaces, and a sample collection tube.

An aliquot of approximately 25 mg of NH_4Cl from step (f) was placed in the large reaction tube. Approximately 5 ml of sodium hypobromite solution (freshly prepared[37] from bromine and sodium hydroxide) was placed in the small side-arm tube. A flask of liquid nitrogen was raised up from beneath the two reaction tubes until both solutions were surrounded, and thus frozen. Stopcocks B and A were then opened, exposing the reaction tubes to the rest of the system, which had been previously evacuated. Stopcock A was closed, the liquid nitrogen removed, and the solutions allowed to melt. Any nitrogen gas from the air which had initially dissolved in these liquids tends to enter the vapor phase above the solutions. The solutions were then refrozen, stopcock A opened, then closed. This cycle was repeated several times to assure complete removal of all air from the samples.

After the solutions had warmed up, the small side tube was rotated 180°, spilling the hypobromite solution into the acidic ammonia solution. The ammonia was oxidized to nitrogen gas according to the following reaction:

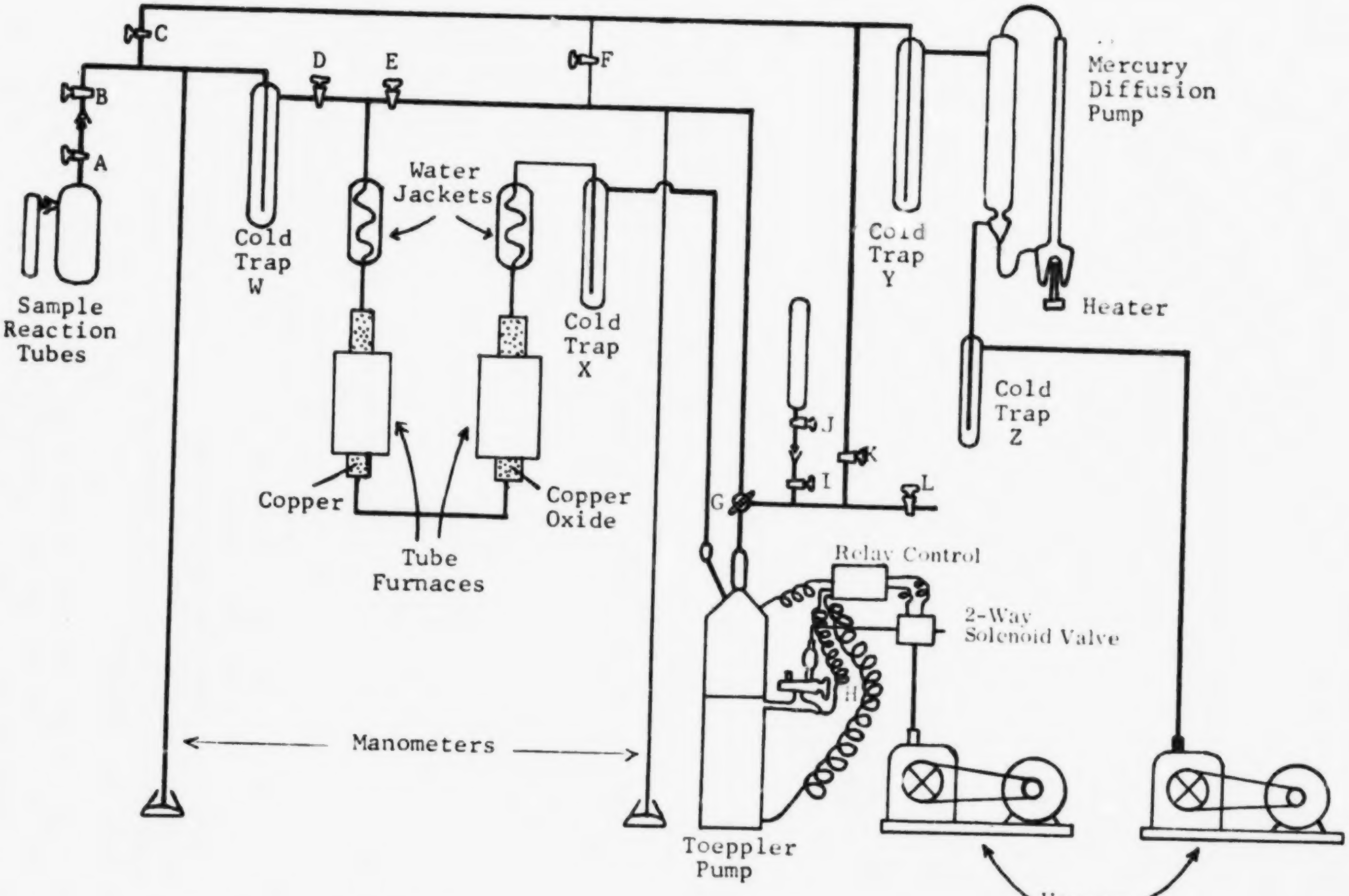
C
B
A
D
E
F
Sample
Reaction
Tubes
Cold
Trap
W
Water
Jackets
Cold
Trap
X
Copper
Copper
Oxide
Tube
Furnaces
Manometers
G
J
I
K
L
Cold
Trap
Y
Mercury
Diffusion
Pump
Heater
Cold
Trap
Z
Relay Control
2-Way
Solenoid Valve
H
Toeppler
Pump
Vacuum
Pumps

Figure 6. Apparatus for Sample Preparation

$$2NH_3 + 3NaOBr = 3NaBr + 3H_2O + N_2$$

The nitrogen gas produced was allowed to pass through stopcocks A and B (stopcocks C and F closed) and into that part of the system containing the furnaces and Toeppler pump. Cold trap W removed water and other condensibles from the gas. The nitrogen gas was then circulated for four hours by the Toeppler pump through the loop formed by the furnaces, cold trap X, the Toeppler pump, and stopcocks G and E. The purpose of this was to remove all oxygen and carbon monoxide from the nitrogen gas. The oxygen was removed by reaction with the copper in one furnace (T=800° C) while the carbon monoxide was removed by reaction with the copper oxide in the other furnace (T=400° C). The carbon dioxide produced by the later reaction was removed at cold trap X. When the gas had been sufficiently purified, three-way stopcock G was turned so that the Toeppler pump forced the gas through stopcocks G, I, and K, into the sample collection tube (stopcocks K and L closed). Stopcock J was then closed and the sample collection tube removed. This tube could be attached directly to an isotope ratio mass spectrometer to permit determination of the N^{15}/N^{14} isotope ratio in the nitrogen gas sample.

Discussion of Sample Preparation

Although quite complex, the above procedure must be strictly adhered to if acceptable results are to be obtained. This procedure was developed and checked with standard nitrate samples. It is important that exactly the same techniques be used from sample to sample. A standard sample (known concentration and isotope ratio) should be run about every fifth sample to insure that no changes have occurred in the preparation or analysis procedures.

Infrared Photography Studies

Both ground and aerial photographs were taken. For reasons discussed in the Introduction, the greatest emphasis was on mesquite trees; however, cotton crops were also photographed. This photography was largely done in the month of July. The cotton crops were approximately half grown.

A frame to hold four cameras was constructed. This permitted simultaneous use of four film or filter combinations. For ground studies this system worked well; however, it proved to be too cumbersome for aerial photography from the plane which was available (Piper Super Cub). Consequently, aerial photographs were taken with single cameras.

In the aerial photography the basic approach was to obtain in a single picture trees or crops exposed to both low and high nitrate areas. This would permit direct comparison of the plants in these areas. Comparing two separate pictures is much more difficult due to differences in sun angle, distance, and exposure; however, this was necessary for the ground shots. Obtaining an aerial photograph of both low and high nitrate areas usually meant including a barnyard in the picture. One problem was in finding a really low nitrate area for comparison. Even though an area a few hundred yards from a barnyard might be low compared to the barnyard, it was still quite high as compared to nitrate observed in other states.[16,17,18] One regular color photograph was always taken to aid in interpreting the infrared color shots.

Two types of cameras were used, Canon FT-QL and Topcon Super-D. The Topcon camera was used with high speed Ektachrome (daylight) rated at A.S.A. 160. The film was developed with Kodak Process E-4 chemicals with no change from the developing instructions. Aerial shots were taken with a glass polarizing filter. A 135 mm lens was used (f/2.8).

The Canon cameras were used with several types of filters, lenses, and film developing procedures. One combination consisted of a Wratten #12 gelatin filter with Ektachrome infrared film. The #12 Wratten filters out everything below 0.50 microns except for 1% transmittance between 0.30-0.34 microns. The film was developed without any change in the developing instructions. A 100 mm lens, f/3.5, was used. All photographs were shot at 1/125 second between f/8 - f/16.

Another combination was an Optics Technology, Inc. (O.T.I.) glass filter and Ektachrome infrared film. This filter had a "window" at 0.70 to 0.74 microns (37% transmittance) with less than 1% transmittance below 0.66 and above 0.76 microns. The film was developed with Kodak E-4 process. The time of the "first developer" was increased by a factor of 1.75. A 55 mm lens (f/1.2) with a 2X Teleconverter was used. All photographs were taken between 1/15 second and 1/60 second at f/2.4.

A third combination was a Wratten 89B filter and Ektachrome infrared film. The 89B filter excludes all radiation below 0.68 microns. The film was developed with Kodak Process E-4 with no change in developing instructions. A 100 mm, f/35, lens was used. All photographs were shot between 1/125 second between f/8 - f/16.

SECTION V

RESULTS AND DISCUSSION

Water Analyses

A total of 233 wells were sampled in this study. The detailed analysis of each sample is too lengthy to present here so they are included in Appendix I. Each well was assigned a well number, and a map at the front of Appendix I gives the well location by number.

In general, the Runnels County groundwater is of poor quality. The U. S. Public Health Service recommended limits for certain species in potable water are given in Table 2. A comparison of the 233 water analyses in Appendix I with these limits reveals that groundwater quality would be very poor even if no nitrate were present, and only 27 of 233 analyses had less than the maximum limit for nitrate. Well 1034, when first checked, had a nitrate content of 3584 mg/ℓ. As far as is known this is the highest nitrate level ever found in a well. After pumping this well for several hours the nitrate level decreased to 2162 mg/ℓ. On the average, Runnels County groundwater considerably exceeds the recommended limit for every species for which a limit has been set. Table 3 gives the high, low, and average concentrations for each species.

Some special analyses were performed in an effort to determine whether the water might be polluted by organic wastes such as septic tanks or barnyards. These are listed in Table 4. Most of these wells were chosen because of their proximity (either near or far) to sources of pollution and because of their nitrate content (either high or low). Ammonia is uniformly low in these samples, as might be expected due to the strong adsorption of ammonia by soil particles. Nitrite ranges from very low to high. The presence of nitrite typically indicates incomplete oxidation of nitrogen containing wastes, i.e., that the wastes are a fairly recent addition. Organic carbon ranges from low to high; however, the large spread obtained in the analysis of the one duplicate sample leaves all these values open to question. Phosphate is uniformly low, again not surprising in view of the high calcium content and relatively high pH of most of these waters (see Appendix I).

Wells tapping limestone aquifers generally had higher levels of nitrate and other contaminants than did wells in

Table 2

U. S. Public Health Service Limits

Species	U. S. Public Health Service Recommended Limit (mg/ℓ)
Nitrate (NO_3^-)	45
Chloride (Cl^-)	250
Fluoride (F^-)	0.7-1.2 (optimum)
Sulfate ($SO_4^=$)	250
Total Dissolved Solids (TDS)	500
Calcium (Ca^{++})	No limit specified
Magnesium (Mg^{++})	No limit specified
Sodium (Na^+)	No limit specified
Bicarbonate (HCO_3^-)	No limit specified
Silicate ($SiO_2^=$)	No limit specified

Table 3
Summary of Water Quality

	Concentration (mg/ℓ)		
Species	Low	Average	High
Nitrate	0.4	287	3584
Chloride	5	471	3100
Fluoride	0.4	2.3	4.8
Sulfate	11	335	1940
Total Dissolved Solids	339	1809	8150
Calcium	64	248	1390
Magnesium	9	91	432
Sodium	8	232	1270
Bicarbonate	31	277	600
Silicate	7	22	44

Table 4

Results of Special Water Analyses

Well No.	NH_3	NO_2^-	NO_3^-	Organic Carbon mg/ℓ	Ortho-Phosphate mg/ℓ
114	<1.0	0.52	136	1	
177	<1.0	0.2	36	1	
182	<1.0	0.82	343	3	<0.2
210	<1.0	<.16	110	5	
264	<1.0	0.29	30	21	<0.2
277	<1.0	1.08	325	1	<0.2
301	<1.0	0.52	221	0	<0.2
591	<1.0	0.36	413	14	<0.2
597	<1.0	<.05	2.5	7	<0.2
727	<1.0	3.2	1302	2	
865	<1.0	1.2	1245	1	
1034 (duplicate)	<1.0	.7	840	35 or 2	
1116	<1.0	0.52	83	14	<0.2

alluvial deposits. This is very likely due to the lower porosity of the limestone, resulting in less opportunity for dilution of contaminants.

Survey of Land Use Practices and Well Data

The results of the survey are presented in Appendix II. The location of the wells is given by the map at the front of Appendix I.

Well Construction

Well construction is generally very poor. Most of the wells are old and have very thin "stovepipe" casing which is easily perforated by corrosion. Almost none of the casings were cemented in to seal off pollution from surface sources or shallow groundwater. Even the newer wells with plastic casings are rarely cemented. In one case (well 365), perched groundwater with a nitrate concentration of 1000 mg/ℓ was draining into the well bore. Although inexpensive, the stovepipe casing and lack of cement have undoubtedly contributed to pollution of some wells.

Terracing

It seems almost certain that the extensive terracing of farming areas resulted in the rise in the water table in 1968-1969. The possible causes of such a rise are fairly limited, and include:

(1) increased percolation of precipitation

(2) infiltration from deeper groundwater

(3) decreased transpiration by plants (phreatophytes).

If the rise were from infiltration, it should have been a slow steady rise over many years since the unplugged shot hole and oil wells have existed for decades. In addition, since the wells were dry in the 1950's the water should be much more saline if it were due to infiltration. Finally, the age of the groundwater (~20 years) as determined by tritium dating is not consistent with the infiltration theory. Some infiltration is very likely occurring, but not enough to account for the widespread rise in the water table.

Plants with very deep tap roots (phreatophytes) which reach the water table can remove large quantities of water by transpiration in dry climates such as Runnels County. The eradication of these plants would remove a loss mechanism for the groundwater, and thus contribute to the accumulation of groundwater. This is unlikely as a major contributor to the groundwater rise, however, since the only widespread phreatophyte is the mesquite, and its eradication has not been that systematic. In addition, some of the most dramatic rises in the water table have occurred in heavily farmed areas which have never had mesquite.

It can be seen from Figure 2 that there were several periods of higher total rainfall than the 67-69 era when the major rise in the water table occurred, thus increased rainfall alone does not seem sufficient to account for the water table rise. The disappearance of many of the creeks in the county in the last twenty years indicates that the relative amounts of percolation and run-off of rain have been significantly altered. The increased percolation due to terracing combined with a period of above-normal rainfall could account for the rise in the water table.

Fertilizer

The land use survey revealed that very little fertilizer is used in Runnels County. The great majority of the farming is dry land farming, and rainfall is too erratic to permit the optimum gain to be realized from fertilizer. In addition, as shown by the soil studies, the soil nitrogen in most areas is already more than adequate.

Waste Disposal

Disposal of animal and human wastes in Runnels County is typical of other rural areas in the state. Only the towns of Ballinger and Winters have sewage systems, thus other areas use septic tanks. The digested liquid from the septic tanks seep into the surrounding soil from these laterals. Part or all of the nitrogen from this liquid is subsequently converted to nitrate. (If all the nitrogen were converted to nitrate, one human could produce approximately 50 pounds of nitrate per year.) Being highly soluble, this nitrate may dissolve in percolating rainwater or in rising groundwater. Nitrate is not strongly adsorbed by soil particles, and moves freely with the water in which it dissolves. Organic matter from the septic tank lateral is usually adsorbed more strongly by soil particles. If the septic tank is located in a soil with some clay content, and if the water table is fairly deep, this "filtering" action by the soil may be quite effective in preventing contamination of groundwater. In limestone, however, where most water transport is through fractures, both nitrate and organic matter may reach the water table. Unfortunately, conditions for effective filtering are not favorable in much of Runnels County.

Barnyards are similar to septic tanks with respect to groundwater pollution except that higher nitrates can be expected since a cow may produce 600 pounds of nitrate per year. Again, limestone formations provide the greatest opportunity for shallow groundwater contamination. In general, the closer a well is to a septic tank or barnyard the greater the opportunity for contamination. Each particular situation depends on the local hydrogeology, well depth, and well construction, however.

Geological and Hydrological Studies

The Colorado River flows west to east through Runnels County and is the major drainage channel. The main tributaries of the river are Oak, Valley, Elm, and Mustang Creeks to the north and Red Bank and Pony Creeks to the south. These creeks and the Colorado River are actively eroding the Permian bedrock. Pleistocene and Recent fluvial and aeolian deposits parallel the Colorado River, with a maximum lateral extent of two miles and a probable maximum thickness of 40 feet. Lithology of the fluvial deposits varies from predominantly clay and silt to sand and gravel. The aeolian deposits are composed of fine-grained quartz sand.

The entire county is underlain by rocks of Permian Age (Figure 7). The rocks strike northeast and dip to the northwest at approximately 40 feet per mile. During Permian time this area was part of the eastern shelf of the Permian Basin. The sedimentary sequence is one of increasing clastic deposition with massive limestones in the lower part of the section grading upward to sandstones and conglomerates in the uppermost section.

The Permian sediments belong to the Wichita-Albany and Clear Fork Groups. According to Beede and Waite[18], formations of the Wichita-Albany Group that crop out are the Bead Mountain Formation, 55 feet of marls and limestone; the Grape Creek Formation, 130 feet of marly limestones and resistant limestones; the Talpa Formation, 400 feet of shales, marls, and limestone; the Clyde Formation, 530 feet of shales, marly limestones, and resistant limestones; and the Leuders Formation, consisting of approximately 190 feet of marly limestones and shales. The formations of the Clear Fork Group that crop out in the area are the Arroyo Formation, 260 feet of shales, marls, limestones, and basal lenses of gypsum; the Vale Formation, 150 feet of shale with a few

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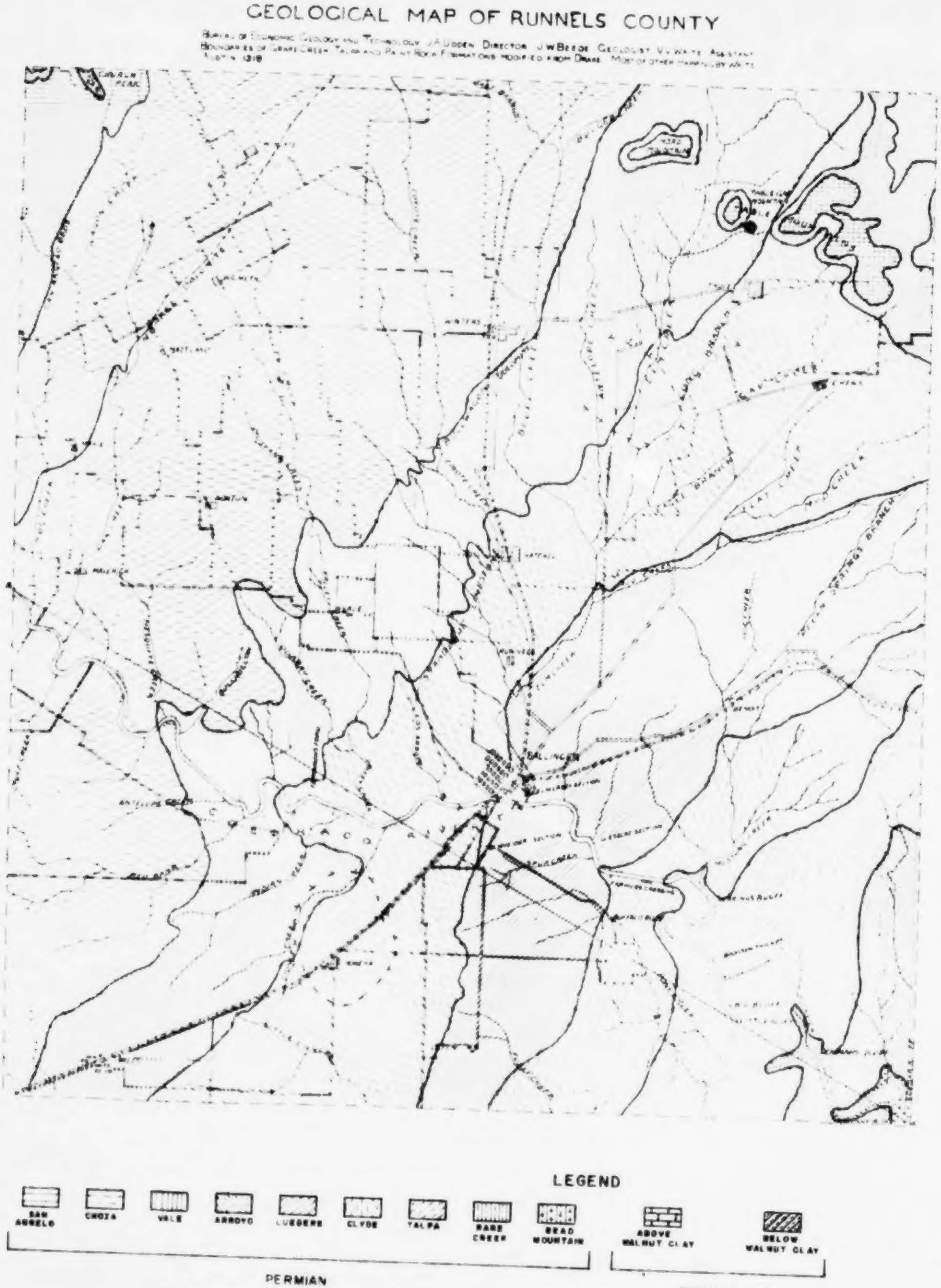

GEOLOGICAL MAP OF RUNNELS COUNTY
Bureau of Economic Geology and Technology J.A. Udden Director J.W. Beede Geologist V.V. Waite Assistant
Boundaries of Grape Creek Talpa and Paint Rock Formations modified from Drake. Most of other mapping by Waite
Austin 1918
BALLINGER
LEGEND
SAN ANGELO
CHOZA
VALE
ARROYO
LUEDERS
CLYDE
TALPA
RARE CREEK
BEAD MOUNTAIN
ABOVE WALNUT CLAY
BELOW WALNUT CLAY
PERMIAN
CRETACEOUS

Figure 7. Geology of Runnels County

sandstone and limestone beds; and the Choza Formation, consisting of 870 feet of red shales with a few limestone and sandstone beds. An outcropping of the San Angelo Formation (175 feet of red sand and silt-stone grading downward into a basal quartz pebble conglomerate) of the Pease River Group occurs in the extreme northwest corner of the county.

Moro and Table Mountains are mesas in the northeastern corner of the county. These cretaceous outliers are remnants of the Edwards Plateau and lie unconformably on the Permian rocks.

Large quantities of Tertiary alluvian cover a large part of the Permian shales and marls of the central region. The alluvium was derived from rocks of the Edwards Plateau and the underlying Permian rocks. The Pleistocene terrace of the Colorado River abuts against this older alluvium along the length of the Colorado River. Valley and Elm Creeks have cut through the alluvium to impermeable Permian shales, causing compartmentalization of groundwater within the alluvium.

The occurrence of groundwater in Runnels County is generally erratic and in most cases of limited quantity. The depth to potable water varies from a few feet to more than 100 feet. Groundwater occurs in Permian limestones and dolomites, basal Cretaceous sandstones, Tertiary alluvium, and Quaternary alluvium. The alluvium supplies the greatest quantities of water. Water quality in general is very poor.

The Permian rocks are, at best, poor aquifers. Aside from yielding only small quantities of water, the water quality is generally poor, with high concentrations of nitrate, chloride, sulfate, and calcium.

Groundwater occurs in solution cavities of the gently-dipping limestones. Cavities form by the differential solution of dense limestone units creating a honeycombed rock, and by solution along joints and bedding surfaces between limestone and marl. Dissolution begins on the bedding surfaces and then dissolves the overlying limestone rather than the underlying marl. Water is commonly encountered beneath hard limestone beds. The situation is illustrated in Figure 8, a measured section from a three foot diameter well.

Initially, neither the dense limestone nor clay-rich marls could have been porous and permeable enough to transport much water. However, after jointing of the limestones,

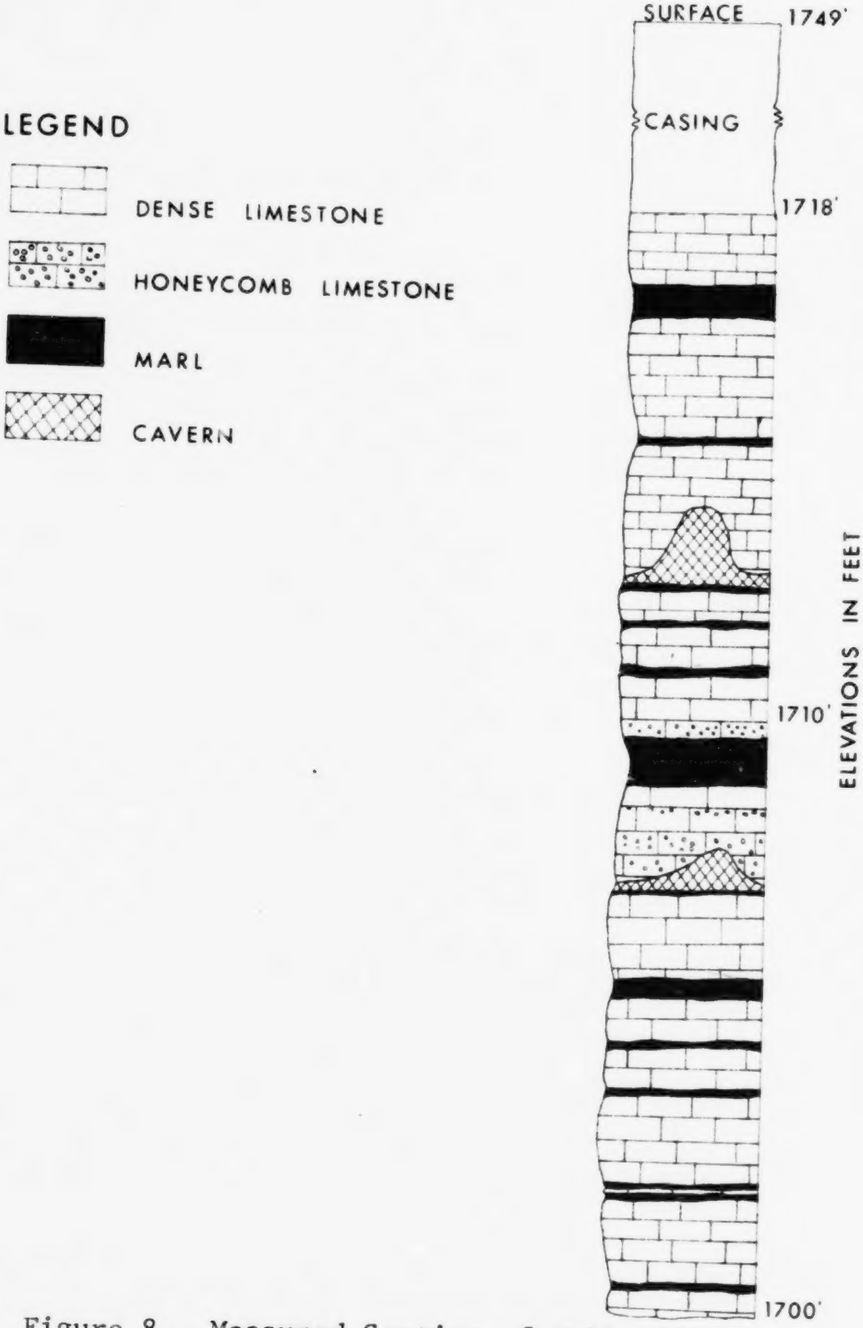

LEGEND
DENSE LIMESTONE
HONEYCOMB LIMESTONE
MARL
CAVERN
SURFACE
1749'
CASING
1718'
1710'
1700'
ELEVATIONS IN FEET

Figure 8. Measured Section of Well 1001

meteoric water was free to flow downward through the joints to the impermeable marl layers where, after long periods of time, groundwater dissolved enough calcium carbonate from the marl and limestone to make the bedding plane a major conduit for groundwater transport. Inasmuch as the joints and bedding plane represent only a few percent of the total volume of the aquifer, little water can remain in storage. Thus, only small amounts of water are available to wells.

Groundwater flow is confined to the natural cavities and artificial cavities that are the results of unplugged seismic shot holes, abandoned oil wells, and poorly-cased water wells. These numerous unplugged holes have interconnected the individual confined aquifers.

The most important sources of recharge are leakage from deep aquifers and precipitation. Unplugged, abandoned oil wells penetrate the Coleman Junction Formation (Permian) at depths of approximately 800 to 2,600 feet. The salty artesian water from the Coleman Junction has sufficient head to flow at the surface and to cause leakage into the shallow aquifers. A few cases of salt contamination of the shallow limestone aquifers have been documented.

Otherwise, the recharge area of these dipping limestone aquifers is limited to where the limestones crop out or are covered by a partially saturated alluvium cover. When rainwater enters the limestone, it flows down-dip where it remains under artesian pressure until tapped by a well. In some places erosion has cut into the limestones, creating seeps or artesian springs. This type of aquifer system is predominant in the southern and eastern part of Runnels County. Residents of this area have long been in the habit of catching rainwater, hauling water, or damming a spring in order to obtain household and drinking water.

Before the extensive terracing, groundwater was discharged by evaporation, drainage into streams, and pumping from wells. Today, however, the major means of discharge are pumping and evaporation. Seeps or bogs are formed where the potentiometric surface intersects the land surface. These seeps occur in depressions, on some hill slopes, and along old stream channels. The seeps undergo a transition; a seep starts fresh, but after a few years becomes extremely salty because of the continual evaporation of the mineralized groundwater. These areas lose their agricultural productivity because the soil is either too salty or too wet.

In Runnels County potential evaporation is far greater than effective rainfall (that part of the rainfall not lost by runoff). According to Kane[14], the average annual net lake surface evaporation from 1940 to 1965 is approximately 60 inches for the Runnels County region. The evaporation of water from plants (transpiration) may be even more important than surface evaporation but is difficult to estimate due to unknown factors such as plant size, plant coverage, and environmental factors such as wind. It would appear that in some years there is little or no water reaching the water table.

At the base of the outliers in northeastern Runnels County are two sandstones known locally as the "Trinity sands". These basal Cretaceous sandstones supply water of excellent quality. Recharge of this aquifer occurs mainly along northern and western outcrops of the sandstone layers, which are generally covered by talus and alluvial gravels. The sands are sealed by impermeable clays and shales and dip slightly to the southeast causing the water to be under artesian pressure. Although adequate for local needs, this aquifer is not significant on a regional basis because of its limited areal extent.

The most important aquifers in Runnels County, in terms of quantity of available water, are the Tertiary and Quaternary alluvial deposits that cover much of the north central part of the county. In general, the alluvium is a mixture of gravel, sand, silt, and clay, with a preponderance of silt and clay. Porosity of the alluvium is estimated to vary from 15 percent to 30 percent compared to an estimated porosity of one to five percent for the limestone-marl system. Thickness of the alluvium varies from zero to approximately 100 feet. The Tertiary alluvium covers a far greater area than the Quaternary deposits and underlies most of the productive farmland in the northern part of the county. In spite of the much larger amounts of water available from the alluvial deposits, the water generally exceeds the Public Health Service limits for chloride, nitrate, and total dissolved solids.

The Quaternary Colorado River terrace sediments provide some groundwater to the total water resources of the southern part of the county but are of minor importance because they are thin (maximum 40 feet) and of limited lateral extent (less than 1 mile). The saturated zone at the base of the terraces is generally less than 10 feet thick. Water wells located on the terraces commonly penetrate the terrace deposits and tap underlying limestone aquifers.

Water Level Recorders

The Texas Water Development Board has maintained two water level recorders in Runnels County since July of 1970 (state well numbers WP 43-15-601 and WP 42-17-701). WP 43-15-601 is located in the west central part of the county (approximately 1 mile due west of Well No. 23) in Tertiary gravels. WP 42-17-701 is located in the south central part of the county in Permian limestone of the Leuders Formation and has Runnels County Well No. 1006.

The water level behavior for both of these wells during the last two years is given in Figure 9. The monthly rainfall during this same period is presented as a bar graph. The extreme limits of the water level during any given month are given by the boundaries of the curve.

It can be seen that small rains during any given month or series of months have very little effect on the water table, probably because of subsequent loss by evaporation. Two consecutive months of heavy rainfall occurred during August and September of 1971, however, and produced a drastic rise in the water table. In WP 42-17-701, the water table did not reach a maximum until November, whereas WP 43-15-601 reached a maximum in September and had decreased appreciably by November. This reflects the difference in depth of the water table in the limestone versus the gravel aquifers. The difference in the change of the water over this time period reflects the difference in the porosity of these aquifers. In the limestone the water level rose eight feet while the water level in the gravel rose four feet. (The exact rainfall and porosity at each site is not known.) Recharge of these aquifers appears quite rapid.

Groundwater Age Dating

The fact that many of the wells in the county went dry during the drought of the 1950's, yet had a very high water level in the late 1960's, would indicate that the water is quite young, assuming the recharge was due to precipitation. The only other possibility is that recharge was due to upward movement of very old water through unplugged oil wells and seismic shot holes. This last situation was considered unlikely since these oil wells and shot holes have existed for many years, while the water table only rose during the 1960's. Several age-dating tests were run to determine the approximate age of the groundwater. Tritium age dating was chosen since this is a good technique for fairly young water and since much of the groundwater occurs in carbonate aquifers which would complicate carbon dating.

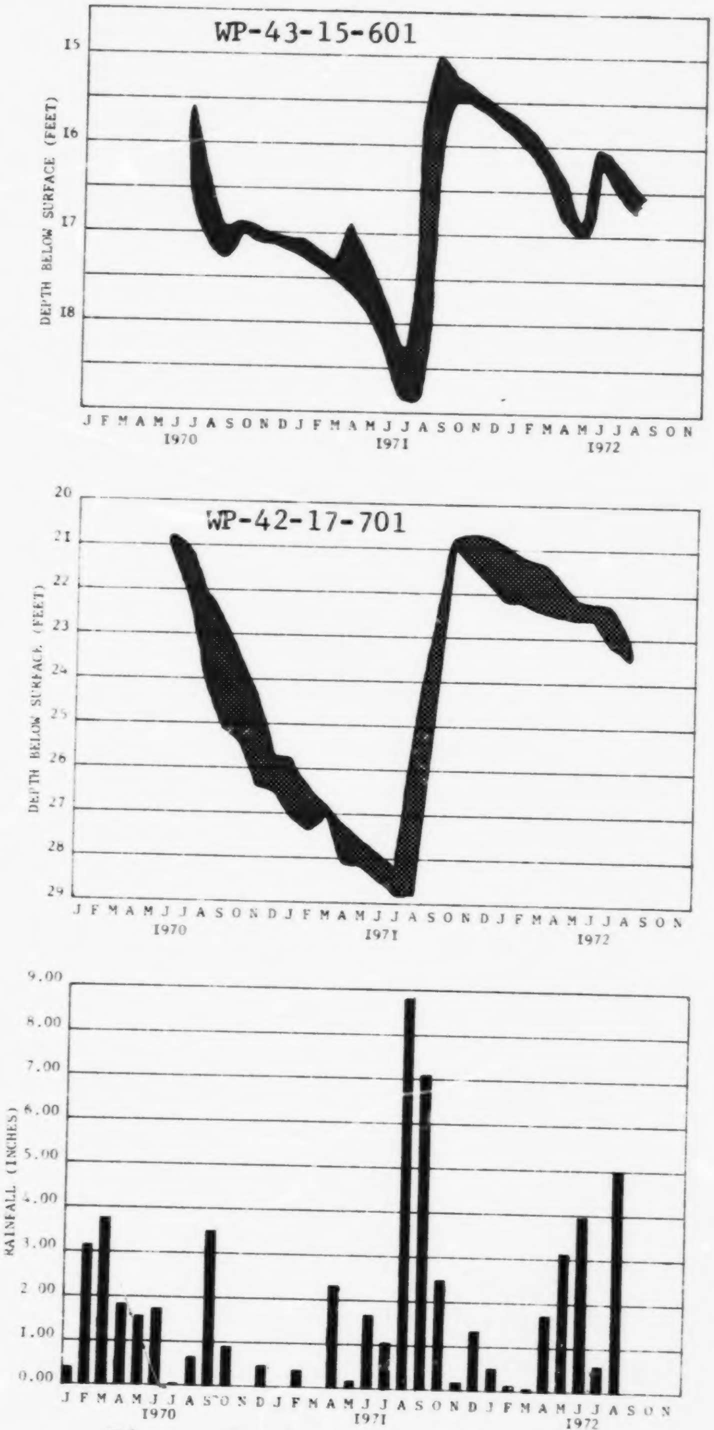


Figure 9. Water Level Recorders

Tritium has a radioactive decay half-life of twelve years, thus the natural tritium content of very old water should be low. A considerable amount of artificial tritium has been added to the atmosphere by thermonuclear explosions since 1952, with a subsequent increase in the tritium content of precipitation. Tritium concentrations greater than 4 tritium units (T.U.) indicate that some recent (~20 yrs.) water has been added to the system. (1 T.U. equals one tritium atom, H^3, per 10^{18} hydrogen atoms.)

It is possible to give a fairly specific age to a groundwater sample if the hydrological conditions are well known, the tritium concentration of the rainwater for the area in question is known for many years, and equations for tritium decay and dispersion in the groundwater are developed. Fortunately, data were available on the tritium content of precipitation in the Runnels County area for the last twenty years. This information was kindly provided by Dr. T. A. Wyerman of the U. S. Geologic Survey, and is shown in Table 5.

Table 5

Tritium Content of Precipitation

Year	T.U.
1952	8
1954	100
1955	16
1956	45
1957	40
1958	160
1959	170
1960	50
1961	70
1962	470
1963	1300
1964	600
1965	270
1966	180
1967	110
1968	90

Two models are available for calculating the tritium concentration now in the groundwater (output tritium concentration) from the tritium content of precipitation (input tritium concentration). The first model is a simple plug flow equation with a radioactive decay coefficient.

$$C = C_o \, e^{-\frac{.693t}{12.5}}$$

where

C_o = input tritium concentration

C = output

t = transit time of the water in the ground

This model assumes no mixing of groundwater of different ages.

The second model, which more likely represents conditions in Runnels County, is a binomial dispersive flow equation with a radioactive decay coefficient.

$$f_o(t) = \sum_{o}^{t} f_i(t-T) \; e^{-\frac{.693T}{12.5}} \binom{n}{x}_T (0.50)^n$$

where

$f_o(t)$ = output function

$f_i(t-T)$ = input function

T = transit time

$\binom{n}{x}$ = binomial coefficient which corresponds to the transit time T

n = function of binomial dispersion

Four water samples were collected for tritium age dating as shown in Table 6. The first three wells are in the southern part of the county. They are well cased and pump from limestone aquifers. These wells are among the deepest wells in that part of the county. The fourth well is in the northern part of the county and taps an alluvial formation.

Estimates of the age of the groundwater from these wells are obtained from Figure 10 which gives curves for the tritium input from precipitation, the tritium output assuming mixing (dispersive flow), and the tritium output neglecting mixing (plug flow). The probable ages of the water samples are shown by the bars in Figure 10 and are as follows:

Table 6
Data for Tritium Age-Dated Wells

Well No.	Owner	Depth	NO_3^-	T.U.
1003	E. R. Holubec	70	820	57 ± 12
552	P. Pieper	75	94	241 ± 11
City of Miles	(Municipal)	130	40	371 ± 13
445	F. Carter	30	120	18 ± 9

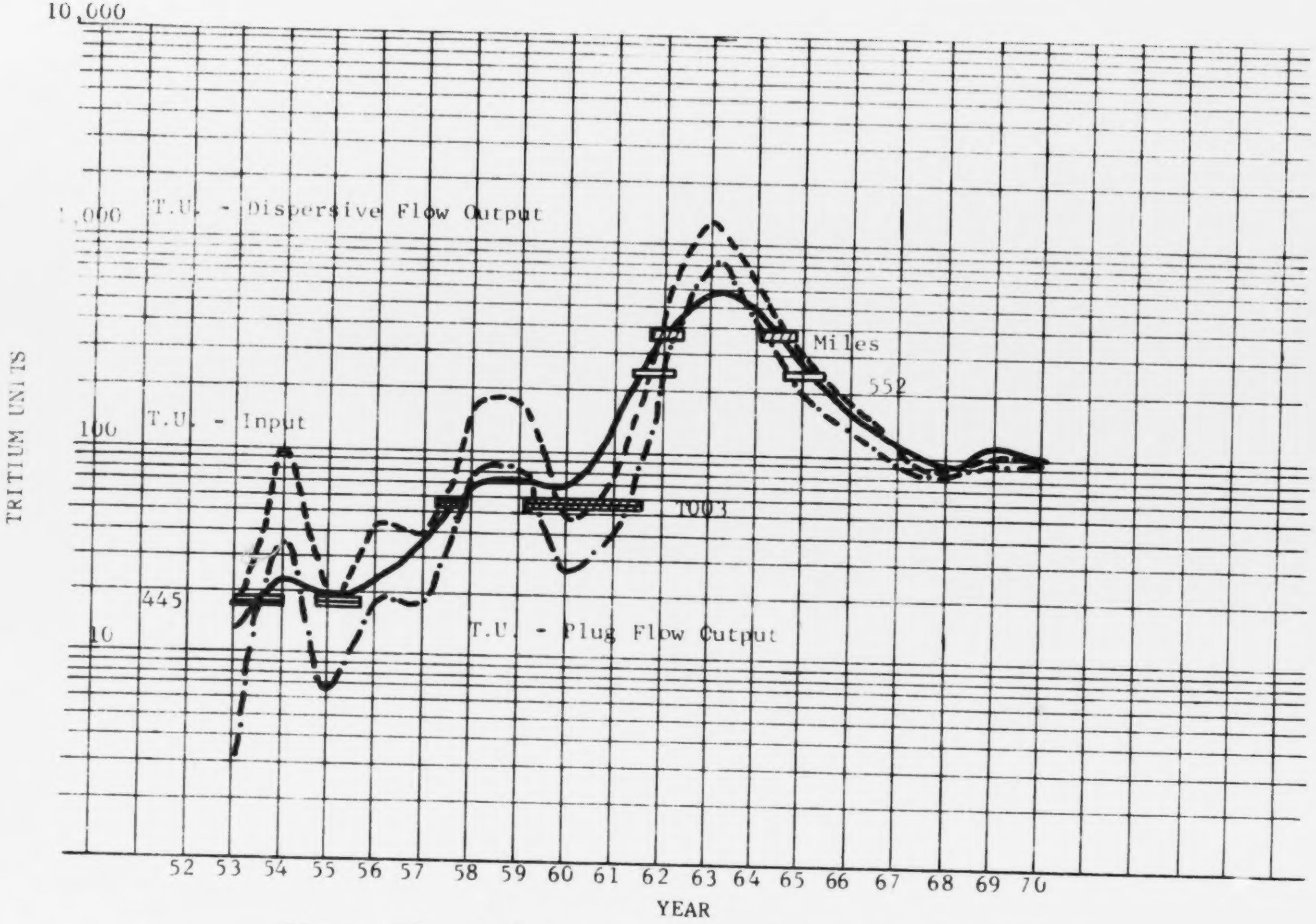


Figure 10. Tritium in Groundwater and Precipitation

Well No.	Probable Age
1003	11-14 years old
552	8-10 years old
City of Miles	8-10 years old
445	16-19 years old

Water Table Map

The information on well altitudes and depths to the water table has been used to determine a water surface map as shown in Figure 11. Since innumerable water wells, oil wells, and seismic holes have penetrated both the alluvium and limestone aquifers, interconnecting the water table and artesian systems, this map is actually a potentiometric surface map (i.e., a map showing both the water table elevations and artesian elevations at one atmosphere pressure). The regional potentiometric surface follows the topography of the land, whereas the local hydraulic gradient may be controlled by pumping wells in the area.

It can be seen that all water drains toward the Colorado River except in the extreme southern edge of the county where it drains toward the Concho River.

Aquifer Tests

Four pumping tests were run to determine storage coefficients and transmissivities. The storate coefficient indicates the amount of water in storage that is released from a unit volume of aquifer per unit decline of head. The transmissivity is the rate of flow of water through a vertical section of an aquifer, whose height is the thickness of the aquifer and whose width is one foot, when the hydraulic gradient is 1.0. The wells which were tested were Well Nos. 67 and 309 in the north part of the county and Well Nos. 552 and 727 in the south part of the county. Well No. 67 was in a calichified gravel, while the other wells tap limestone aquifers. The results of the aquifer test are shown below.

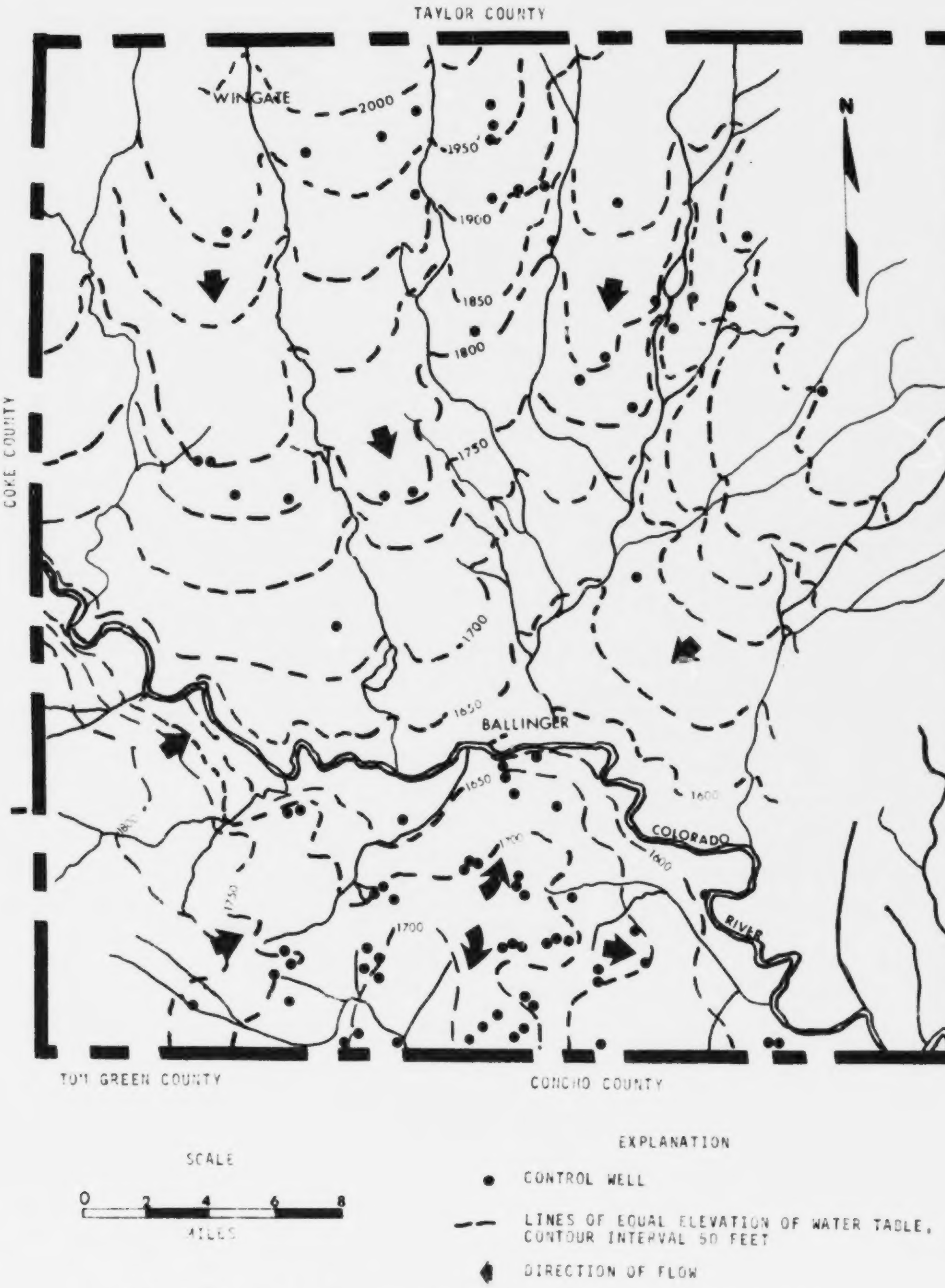

TAYLOR COUNTY
WINGATE
2000
1950
1900
1850
1800
1750
1700
1650
BALLINGER
1600
COLORADO
RIVER
1800
1750
1700
1700
1650
1600
N
COKE COUNTY
COLEMAN COUNTY
TOM GREEN COUNTY
CONCHO COUNTY
EXPLANATION
SCALE
0
2
4
6
8
MILES
CONTROL WELL
LINES OF EQUAL ELEVATION OF WATER TABLE, CONTOUR INTERVAL 50 FEET
DIRECTION OF FLOW

Figure 11. Potentiometric Water Level Map

Well No.	Well Depth	Depth to Water	NO_3^- (mg/ℓ)	Coefficient of Storage	Transmissivity (gal/day/ft)
727	70	---	1260	6×10^{-5}	15,000
552	70	28	94	4×10^{-4}	6,500
309	60	33	294	5×10^{-5}	670
67	67	8	288	1×10^{-3}	80,000

Soil Nitrate Studies

The simultaneous nature of the rise in the water table and the onset of the nitrate problem in Runnels County strongly suggested that nitrate in the soil had been leached from zones previously above the water table. Eighty-four holes were drilled in Runnels County to investigate the nitrate content of the sub-surface soils. The data are presented in terms of "profiles" of nitrate concentration with depth. The lithology of the soil formation at the hole site is also shown as a function of depth, and was determined by an examination of the collected soil samples. Because of the large number of these profiles, only a few of the most interesting will be presented here. The rest are contained in Appendix III and Appendix IV. A brief discussion of each profile is given. The profiles in Appendix III show both nitrate and chloride profiles except where chloride concentration is less than 18 mg/kg. The profiles in Appendix IV show nitrate only. An index to the lithology is given in the first of each Appendix. The location of most holes is given with respect to a water well whose location is given by the map at the first of Appendix I. To aid in interpreting the effect of a nitrate profile on the groundwater, the nitrate concentration and depth to the water table are given for the well used as a reference. (When the lithology is not completed to 20 feet, this indicates water was encountered at the depth where the lithology stops.) The difference in the water table as measured in the well (as reported in Appendix II) and in the hole may be due to the well being under artesian pressure, or the fact that the holes were generally drilled months after the well was inventoried.

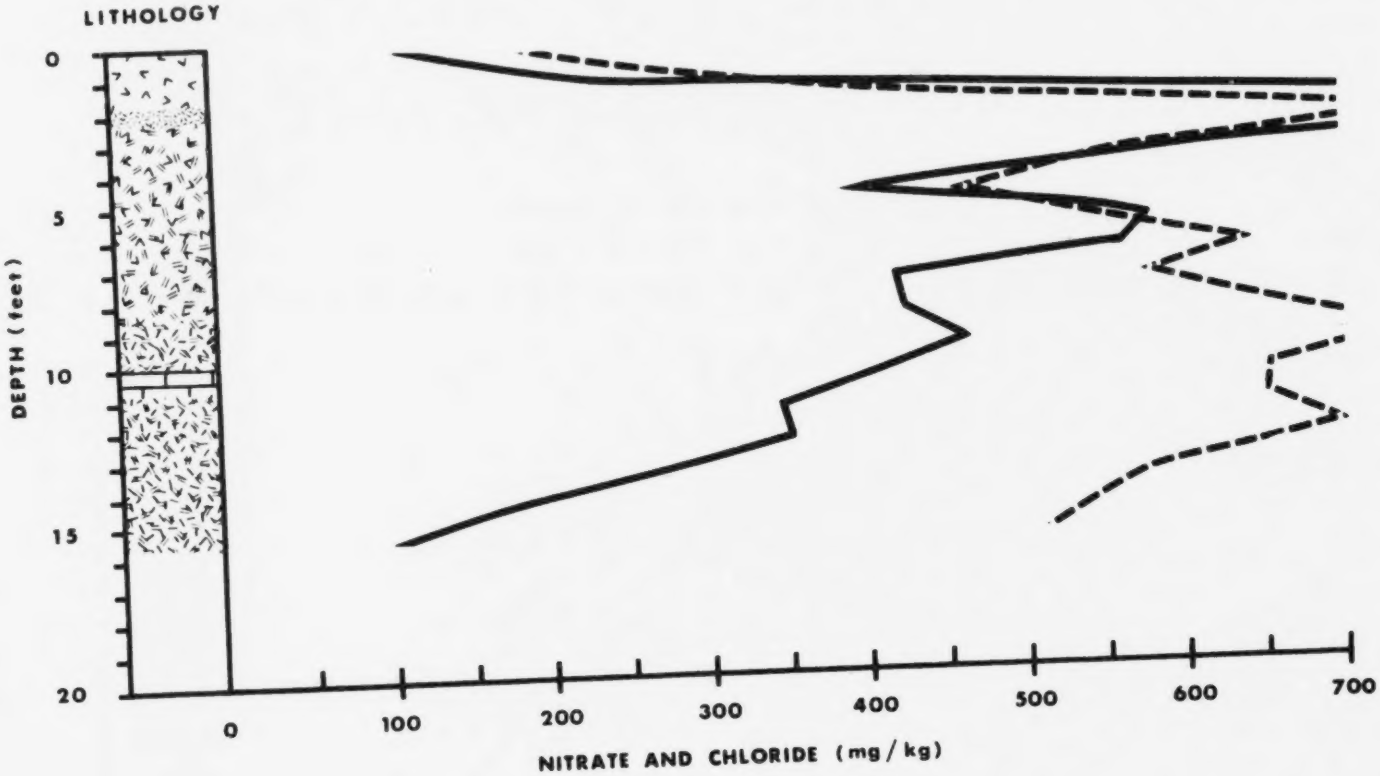
An average value for the number of pounds of nitrate per acre-foot was determined for each profile. For holes in fields and pastures these numbers are probably representative of the quantity of nitrate actually present beneath an acre of ground in that vicinity. However, for holes near septic tank laterals and in small barnyards these numbers may be inaccurate due to the probability of high localized concentrations at the site of the hole. No chloride profiles are given with the nitrate profiles in Appendix IV. Hole locations are given with the profiles. Again, an index to the lithology is given at the first of Appendix IV.

Fourteen holes were drilled in or immediately adjacent to barnyards. Only two of these holes exhibited less than 11,000 lbs. of nitrate per acre for a depth of 15 feet (holes 83 and 84). Three holes (40, 41, 43) drilled in different parts of an old barnyard yielded 40, 59.5 and 70 thousand pounds per acre for a 15 foot depth. Nitrate beneath barnyards seems to always be accompanied by high chloride concentrations. Figure 12 shows the nitrate and chloride profiles for hole 40. It can be seen that a good correlation exists between nitrate and chloride, as is expected when contamination is due to animal wastes. Note also the shallow water table. A rising water table at this site would surely dissolve considerable quantities of nitrate. The big decrease in soil nitrate between 13 and 15 feet might occur because the water table has previously risen into this zone and dissolved part of the nitrate.

Three holes were drilled next to septic tank laterals (holes 24, 25, and 44). All three exhibited nitrate peaks at shallow depths and good correlation between nitrate and chloride. Figure 13 shows the profile for hole 25. Again, note the shallow water table (12 feet).

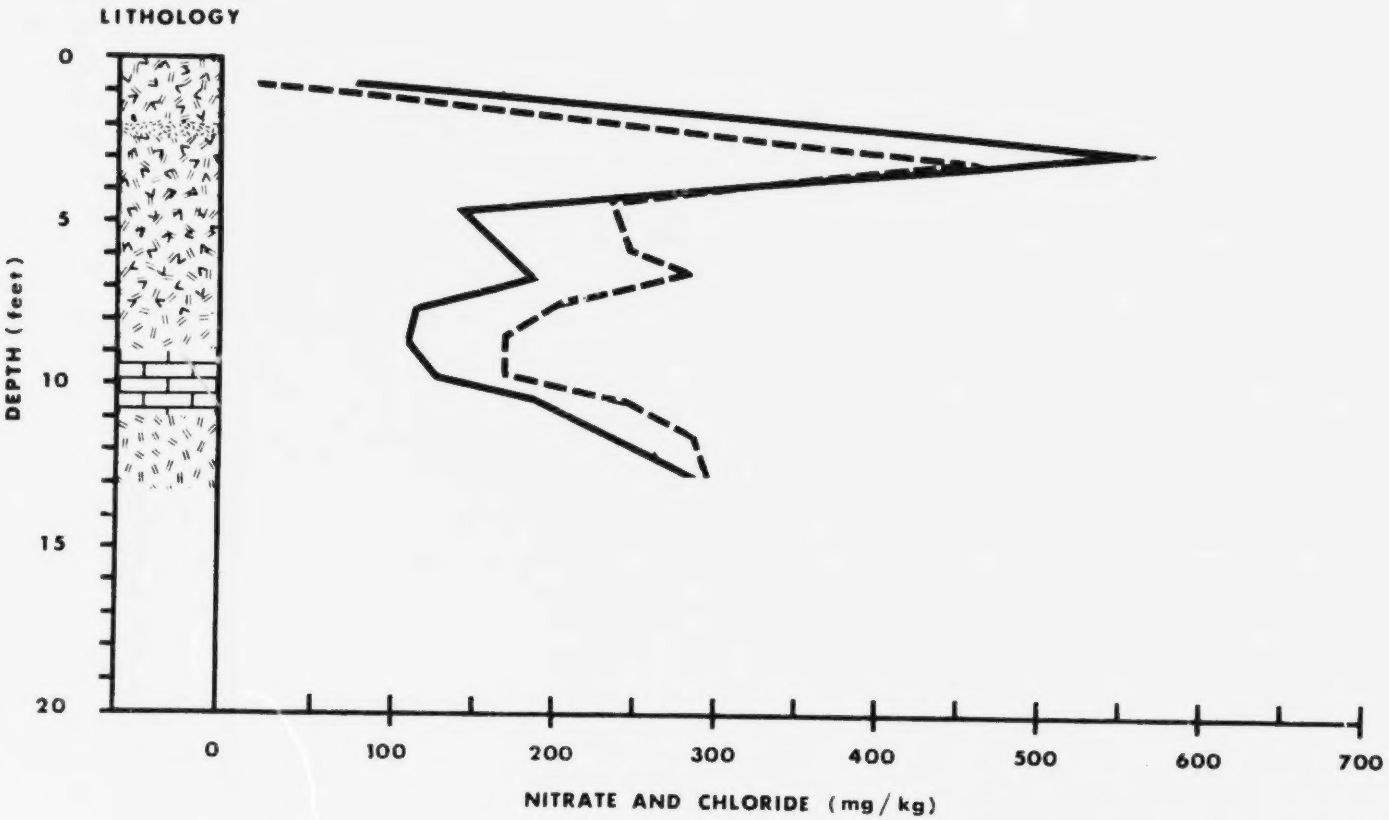
Thirty-three holes were drilled in pastureland. In most cases this land has been used for grazing livestock. The highest value observed (hole 45 with 14,300 #/acre/15 feet) was reportedly near a watering hole for cattle drives during the early 1900's. The lowest value observed in this study was for hole 60, with 600 #/acre/15 feet. However, two other holes in the same pasture (54 and 55) had 4,300 and 4,400 #/acre/15 feet. Figure 14 shows the profile for hole 4, which is located in a mesquite pasture. This profile shows high nitrate below 15 feet, with no associated chloride.

Twenty-six holes were drilled in cultivated fields. The lowest value found was for hole 62 with 1350 #/acre/20 feet. The two highest values were 17,300 #/acre/15 feet for hole 46, located in a cotton field near an old watering hole, and 14,200 #/acre/15 feet for hole 12, also located in a cotton field. The profile for hole 12 is shown in Figure 15. Note again the absence of chloride. There is no history of any cattle, fertilizer, or human habitation near this site.



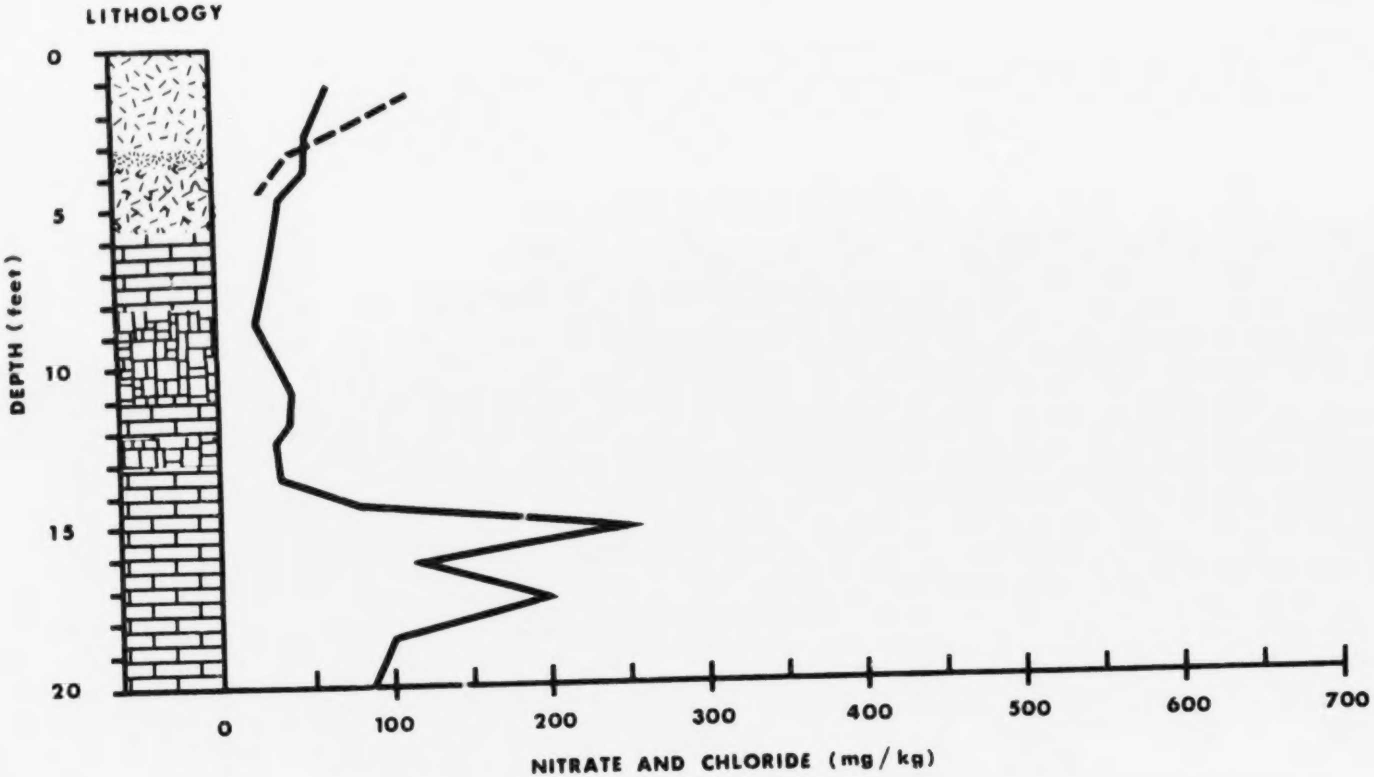
Hole 40. Located 100 feet north of well 551 (294 ppm nitrate, 56 feet to water) in a barnyard. Nitrate and chloride are very high. 2667 #/acre-foot.

Figure 12. Nitrate and Chloride Profiles for Hole 40



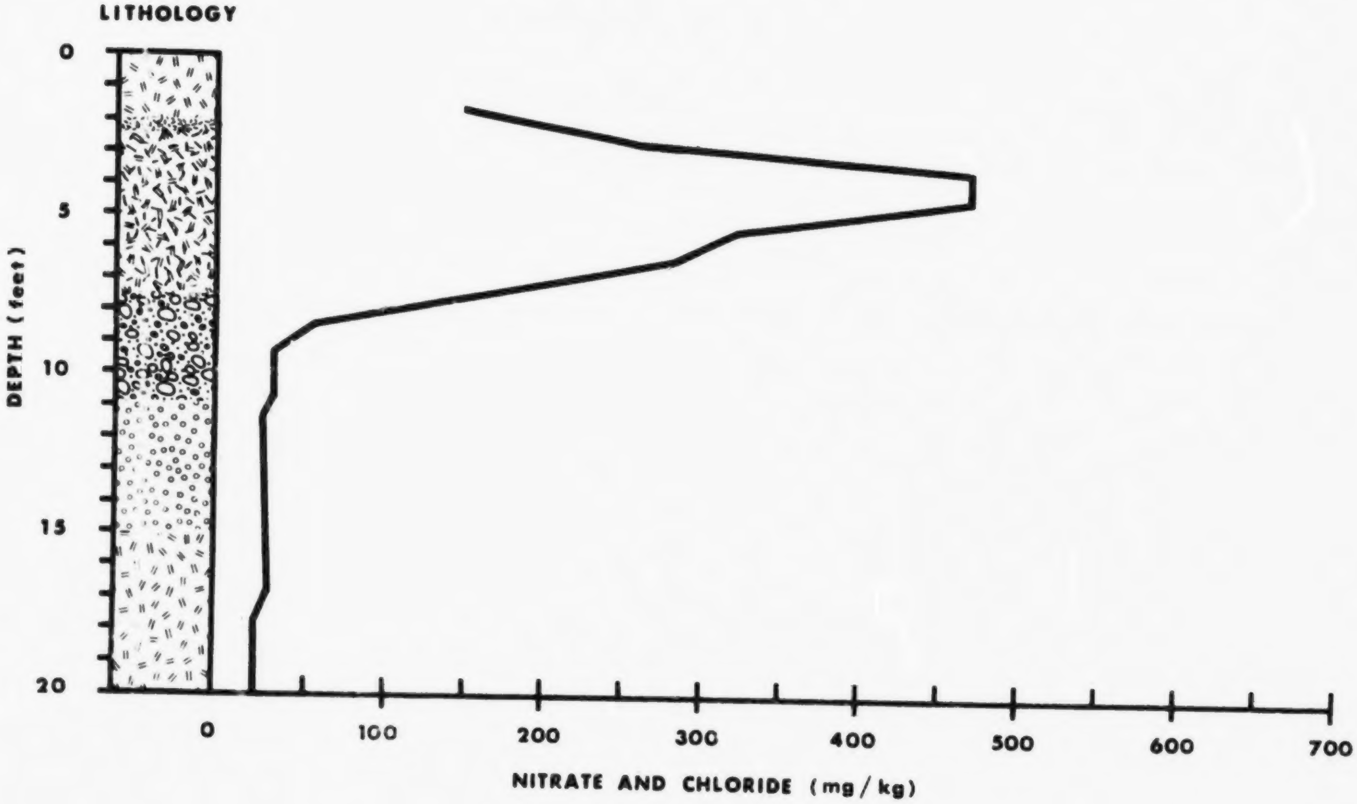
Hole 25. Located 2 feet east of a septic tank lateral, 10 feet south of hole 24, and 50 feet northeast of well 867 (1898 ppm nitrate, 6 feet to water). High nitrate and chloride. 1067 #/acre-foot.

Figure 13. Nitrate and Chloride Profiles for Hole 25



Hole 4. Located in a mesquite pasture ¼ mile west of well 419 (240 ppm nitrate) (see map following Hole 5). The high nitrate concentration below 14 feet is possible due to deposition from groundwater flowing laterally in a permeable limestone. The chloride is very low. 327 #/acre-foot.

Figure 14. Nitrate and Chloride Profiles for Hole 4



Hole 12. Located on a turn row in a cotton field ¼ mile south of well 234 (387 ppm nitrate, 12 feet to water). There is no history of livestock, fertilizer, or human habitation at this site. Chloride is very low and nitrate is very high. 947 #/acre-foot.

Figure 15. Nitrate and Chloride Profiles for Hole 12

The nitrate content of the soils at the various sites is summarized in Table 7.

It is worthwhile to examine the results of other studies on soil nitrates. Table 8 gives some soil nitrate values which were calculated from data from three other studies. It can be seen that the nitrate levels in Runnels County are much higher than for these other studies, in most cases by an order of magnitude. The type of soil for the Illinois data is not reported.

There is some question about how much significance can be attached to the depth at which a particular "peak" occurs in a nitrate profile. It seems likely that much of the nitrate is held in solution in films of moisture on soil particles, and these films may migrate upward or downward depending on climatic conditions.[19]

The eighty-four holes which were drilled revealed that most of the soils in Runnels County contain large amounts of nitrate. The highest nitrate soils were beneath barnyards, e.g., holes 13, 21, 22, 32, 40, 41, 43, 47, 57. In some cases the nitrate was high for almost the entire depth of the hole (40, 41, 43) while in other cases distinctive peaks existed at some depth (holes 13, 21, 47, 57). The only barnyard which exhibited a uniformly low nitrate content was hole 84. No reason for this is apparent. Barnyard soils always exhibited a high chloride content which correlated well with the nitrate. The relative amounts of chloride and nitrate were by no means constant, but peaks for each usually existed at the same depths. Possibly, the actual amount of chloride present is strongly dependent on the chloride content of the water supply for the cattle. The actual amount of nitrate present probably depends on many factors. A series of chemical reactions are required to convert the organic nitrogen in cattle wastes to nitrate. Many of these reactions are induced by bacteria, the type of which might vary from one soil to another. In addition, one of the intermediate compounds is ammonia (NH_3) which has a high vapor pressure and could easily be lost into the atmosphere, especially if the soil is dry. If conditions become anaerobic — e.g., after the soil became saturated by rainfall — denitrifying bacteria could convert nitrate or nitrite to nitrogen gas. Thus the fraction of the nitrogen in animal wastes which actually gets converted to nitrate could be highly variable. Chloride ion is relatively inert, however, and shoult not undergo any redox reactions or any "loss" mechanisms.

As discussed earlier, it is not clear whether the depth at which a nitrate peak occurs is any indication of the age of that nitrate. Some barnyards and farmsites which had been

Table 7

Pounds Nitrate Per Acre-Foot

Hole	Nitrate	Hole	Nitrate	Hole	Nitrate	Hole	Nitrate
1	2080	22	2000	43	5270	64	62
2	247	23	1060	44	313	65	85
3	510	24	2130	45	953	66	110
4	326	25	1070	46	1150	67	200
5	247	26	400	47	1150	68	88
6	180	27	213	48	345	69	286
7	426	28	253	49	275	70	65
8	287	29	160	50	125	71	212
9	167	30	293	51	240	72	245
10	173	31	454	52	178	73	112
11	113	32	1540	53	130	74	73
12	944	33	1340	54	215	75	70
13	1380	34	354	55	220	76	66
14	240	35	387	56	263	77	100
15	760	36	260	57	945	78	82
16	735	37	247	58	160	79	75
17	360	38	548	59	50	80	65
18	1100	39	447	60	40	81	70
19	248	40	2670	61	172	82	110
20	240	41	3970	62	67	83	155
21	1740	42	1330	63	92	84	87

Table 8

Soil Nitrate in Other Areas

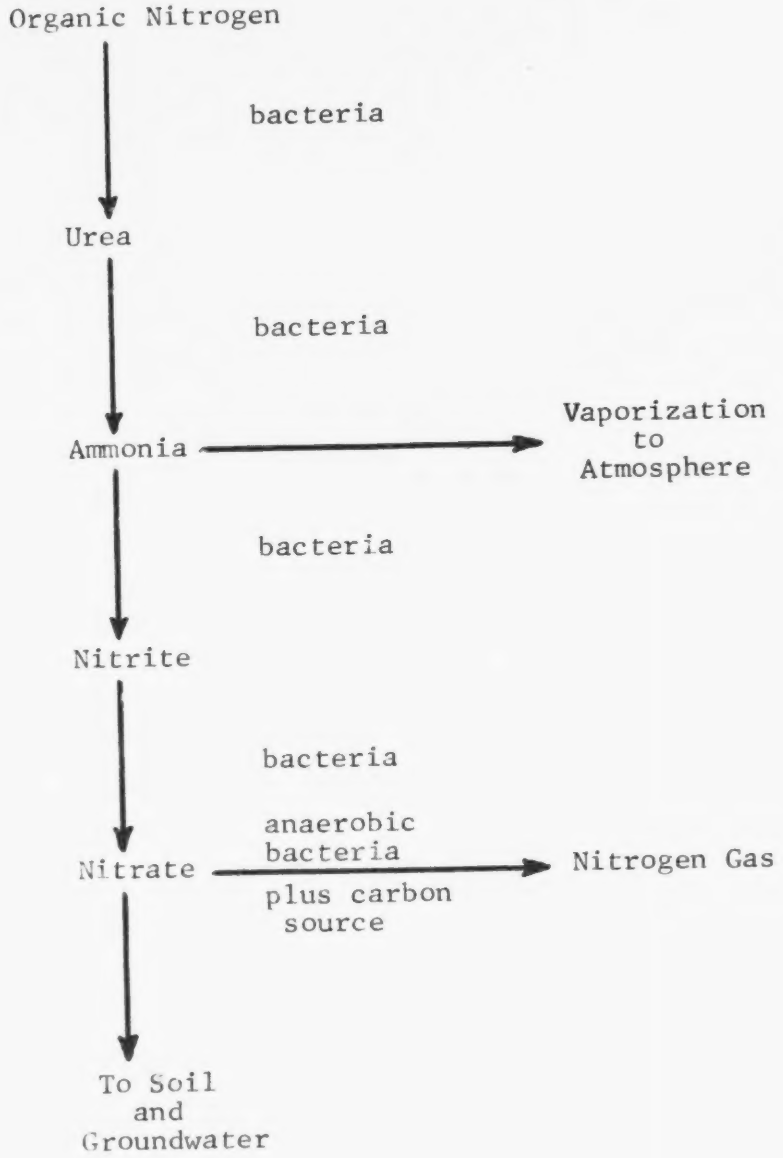
Investigator	Location	Pounds Nitrate Per Acre-Foot
Stewart *et al*., 1968 (Colorado)	alfalfa	4
	native grass	4
	cultivated dry land	13
	irrigated land	25
	corrals	72
Smith, 1969 (Missouri)	cultivated field	13
	cultivated field	14
	feedlot A	145
	feedlot B	200
	feedlot C	21
	feedlot D	66
	poultry yard	59
Harmeson *et al*., 1970 (Illinois)	soil A	82
	soil B	125

deserted for many years exhibited high nitrate at shallow depths (holes 33, 38, 45, 46).

Nitrate profiles near septic tank laterals typically exhibited a peak at shallow depths (holes 24, 25, 44). Chloride correlated well with the nitrate present.

Some surprisingly high nitrate levels were found under pastures and cultivated fields. The most remarkable thing about the soil studies was the finding of relatively high nitrate concentrations without associated chloride (holes 2, 4, 5, 7, 12, 34, 35). The lack of chloride indicates the source of this nitrate is not animal or human wastes. It is difficult to see how chloride could have been removed if it were originally present with this nitrate. Chloride compounds are typically very soluble, so precipitation seems unlikely. It also is unlikely that the nitrate could be retained in the soil by adsorption while the chloride was flushed down (lateral movement is unlikely in the unsaturated zone) into the groundwater. Nitrate is notable for its resistance to adsorption. As noted earlier, chloride is very stable, so it is unlikely that it could be removed by some chemical reaction (e.g., conversion to chlorine gas). In addition, chloride is observed with nitrate in other areas such as barnyards, thus there does not seem to be a tendency for chloride to be so strongly adsorbed by soil particles that it is not detected in solution. The most reasonable explanation is that no chloride was deposited with this nitrate. In general, nitrate is slightly higher under cultivated fields than under pastures (where cattle normally graze). This also makes animal wastes suspect as the source of the nitrate. In addition, the highest chloride-free nitrate profile (hole 12) occurs where there is no history of any livestock.

As compared to the results of studies in other states, nitrate under fields, pastures, and barnyards is very high in Runnels County. It is somewhat difficult to make meaningful comparisons of total nitrate under barnyards without knowing the time the barnyards were used, the rainfall, and the average number of cattle that were contained. Most of the Runnels County barnyards are quite small and are on farms where a limited number of cattle are raised. The barnyards are actually occupied only intermittently by the cattle and do not serve as true feedlots. Given these conditions, it is surprising that the nitrate should be higher under the barnyards in Runnels County than under feedlots in Colorado. The fact that nitrate is much higher under both fields and barnyards is significant and indicates that the soil environment in Runnels County somehow causes a maximum amount of whatever nitrogen reaches the soil to be converted to nitrate. As noted earlier, reduced forms of nitrogen must go through a series of reactions to be converted to nitrate. These can be shown schematically as follows:


Organic Nitrogen
bacteria
Urea
bacteria
Ammonia
Vaporization to Atmosphere
bacteria
Nitrite
bacteria
Nitrate
anaerobic bacteria
plus carbon source
Nitrogen Gas
To Soil and Groundwater

It can be seen that organic nitrogen (from plants or animals) may end up as ammonia in the atmosphere, as nitrogen gas in the atmosphere, or as nitrate in soil or water. It would appear that conditions in Runnels County must minimize loss as ammonia and as nitrogen gas. Possibly, conditions under feedlots become anaerobic permitting loss of most nitrogen as nitrogen gas, whereas intermittently used barnyards do not become anaerobic; thus, soil nitrate under barnyards is very high. Such a mechanism does not account for the high nitrate observed under fields and pastures, however.

Unlike the case for barnyards, nitrate under fields and pastures can be directly compared to other ateas. The high nitrate in Runnels County also indicates that formation of nitrate must be encouraged by environmental conditions in Runnels County. The number of sources of this nitrate is fairly limited and includes:

(1) degradation of plant protein (organic nitrogen)

(2) fixation by leguminous plants (symbiotic bacteria)

(3) fertilizer

(4) fixation by free-living bacteria

(5) formation from animal wastes (cattle or buffalo)

(6) formation from organic-rich shales

(7) accumulation from nitrogen in rainfall.

The degradation of plant proteins should go through the same series of reactions outlined earlier with the same potential loss mechanisms for ammonia and nitrogen gas. Every fall plants die, and the plant protein may be converted to nitrate. If this nitrate remains in the root zone it may be taken up in the spring by new plants and reconverted to plant protein. However, some of the nitrate may be washed down below the root zone by winter rains. The gradual accumulation of this nitrate over many years might account for the soil nitrate observed in Runnels County. Just how much chloride should be associated with such nitrate is not known.

The only leguminous plant of any consequence in the study area is the mesquite tree. Although abundant in some areas, many of the fields and pastures where appreciable nitrate levels occur have never had mesquite as far as is known, and definitely not for the last hundred years. Because of this legumes are considered an unlikely source of the nitrate.

Fertilizer is used very rarely in cultivated areas in Runnels County, and not at all in the pastures, and is thus not a possible source of the large quantities of nitrate which have been observed.

There are certain forms of free-living (non-symbiotic) bacteria which can convert nitrogen gas into other nitrogen compounds. A study of the microbiology of Runnels County soils was beyond the scope of this work, but such bacteria are a possible source of the nitrate. The fact that nitrate levels under barnyards are unusually high in comparison to other areas argues against this, however, unless these bacteria could somehow thrive beneath a barnyard. The most consistent explanation for the fact that nitrates are high both under barnyards and in fields and pastures is that the environment somehow encourages conversion of all available nitrogen to nitrate.

The nitrate observed beneath what are presently cultivated fields could conceivably be the result of animal wastes (either cattle or buffalo) which were deposited before the land was converted to farming. However, there are altogether too many holes which have relatively high nitrate levels but very low chloride levels to support this theory. As discussed earlier, it is difficult to visualize any mechanism by which the chloride could have disappeared yet left the nitrate behind. This is therefore considered an improbable source.

Some deposits of shale have a relatively high content of organic matter, which in turn may contain appreciable amounts of nitrogen. The oxidation of this organic nitrogen could yield nitrate. This is considered to be an unlikely mechanism since nitrate occurs in many areas where no shale exists at shallow depths.

Rainfall contains some nitrogen, principally in the form of ammonia and nitrate. Lightning is typically cited as a source of nitrogen fixation, but some workers believe the contribution by lightning is minimal.[20,21,22,23] As discussed earlier, some ammonia probably escapes into the air from decomposition of plant and animal protein. Wind-blown soil could contain nitrate.[24] Both ammonia and nitrate are very soluble, and will be removed from the air by rainfall. According to Junge[25], average nitrage and ammonia concentrations for a period of a year in West Texas were approximately 1 ppm nitrate and 0.1 ppm ammonia. Assuming all the ammonia is converted to nitrate this could add almost two pounds of nitrate per acre to the soil in a year of average rainfall (22.6 inches). Since this is only a tiny fraction of the actual nitrate observed, this is considered an unlikely source of the nitrate.

The situation as developed by the subsurface soil studies can be summarized as follows. Nitrate in Runnels County is quite high in comparison to other areas. There is no apparent reason to believe that the total nitrogen introduced into the soil every year in Runnels County is greater than in other areas. In fact, for areas which are heavily fertilized, it would seem that the nitrogen added in Runnels County would be small in comparison. Therefore, the high nitrate in Runnels County can only be explained if the environment is such that a greater fraction of the available nitrogen is converted to nitrate and that nitrate is not subsequently flushed down into the groundwater. The most reasonable way for this to happen is if (a) ammonia is adsorbed unusually strong and not lost by evaporation, (b) loss of nitrogen by denitrification under anaerobic conditions is rare, (c) climatic conditions are such that net percolation from surface to water table is very small, except at selected areas such as behind terraces or through fractures in limestone. (It is interesting to compare hole 72, which is midway between terraces with hole 73, which is behind a terrace. Though both holes are in the same field, hole 72 has 4,900 pounds of nitrate per acre while hole 73 has only 2,250 pounds per acre. Increased percolation at hole 73 with subsequent leaching of nitrate could account for the difference.)

One point is noteworthy regarding the soil studies. Few areas have been studied as thoroughly as Runnels County, and this study in all likelihood came about because of the rise in the water table which caused leaching of the nitrate. There is a very good chance that the conditions in Runnels County which led to the accumulation of the nitrate in the soil are not unique.

Nitrogen Isotope Ratio Studies

Denitrification in Well Bore

Pumping the well before collection of the sample was found to be important for getting a nitrogen isotope ratio which accurately represented the groundwater, especially if the well construction invites surface contamination. Table 9 shows data for three such wells which had not been pumped for a long (unspecified) time.

Table 9
Isotope Ratio Data for Pumped Wells

Well	Condition	Nitrate (mg/ℓ)	δ
141	Not pumped	141	- 3.1
141	Pumped	211	+ 7.5
388	Not pumped	63	- 6.0
388	Pumped	978	+10.3
1004	Not pumped	186	- 1.8
1004	Pumped	250	+10.4

All three of these wells increased in nitrate content after pumping, indicating that denitrification has been occurring in the well bore. Denitrification requires a source of carbon so contamination by organic materials from a surface source is indicated. The direction of the change in the δ value is somewhat surprising since the remaining nitrate (after denitrification) appears to be enriched in N^{14}, thus indicating that N^{15} is favored in the denitrification reaction.

As discussed earlier, the basic approach was to compare the isotope ratio of nitrate from groundwater to the isotope ratio of nitrate taken from the soil at sites where the source of the nitrate could reasonably be predicted.

Nitrogen Isotope Ratios for Groundwater

Table 10 lists the isotope ratio in terms of the δ value for the nitrate from 33 water wells. A positive δ value indicates the nitrate is enriched in N^{15}. The nitrate concentration for the period 1969 to 1972 is also shown.

One important observation regarding this data is that very high nitrate concentrations always have high δ values. Note also that on the average, nitrate concentrations have shown an encouraging drop during the last several years. Such a decrease could be due to dilution by freshly infiltrated (but relatively uncontaminated) water or could be due to mixing of highly contaminated water from the top of the water table (where the leaching occurred) with less contaminated water at the bottom of the aquifer.

Table 10

Isotope Ratio Data for 33 Wells

Water Well No.	Owner	δN^{15}	(NO_3)mg/ℓ		
			1972	1971	1969
15	Steinback (windmill)	+ 3.25	200	340	280
16	Steinback (pressure)	+ 2.0	243	250	220
18	A. Halfman (windmill)	+ 6.4	288	791	540
67	C. Robinson	+ 7.52	154	238	330
105	Connelley	+ 7.36	21	>.4	56
211	R. Hohensee	+ 7.5	211	220	320
165	Nitsche	- 1.08	78	326	490
201	H. Book	+ 2.17	96	220	130
233	W. Beimer (windmill)	+ 7.0	416	572	600
234	W. Beimer (pressure)	+ 3.3	290	378	390
301	R. T. Odell (spring)	+ 6.32	175	240	245
309	L. Harter	+ 4.5	390	294	233
366	Kvapil (windmill)	+ 2.5	32	56	62
369	W. Ransbarger (windmill)	+ 7.0	257	326	380
386	E. O. Eggemeyer (house)	+ 5.8	366	315	310
388	E. O. Eggemeyer (barnyard)	+10.3	978	1428	
419	Busenlehner (house)	+ 5.3	186	240	250
421	Busenlehner (mesquite)	+ 8.6	105		
506	B. Wilde	+ 5.2	174	299	300
551	Pieper (house)	+ 6.64	184	294	200
551a	Pieper (seep)	+ 8.3	470		
552	Pieper (irrigation)	+ 1.17	94		
728	Teplicek (irrigation)	+ 2.7	61	130	
865	O. Halfman (house)	+14.1	1360	1360	
865	O. Halfman (house)	+13	1260		
865	O. Halfman (house)	+13.2			
867	O. Halfman (barn)	+10.4	579	1898	
868	O. Halfman (irrigation)	+13.13	21		920
1002	R. Schwertner	+ 4.96	223	280	
1003	E. Holubec	+ 6.28	255		
1034	F. Bachous	+12.0	1238	2162	2240
1004	W. Lange	+10.4	250		
Town of Rowena	Carl Wilde	+ 5.8	75		

Nitrogen Isotope Ratios for Soil

Several holes were drilled and soil samples collected every foot. Isotope analysis of nitrate from these samples was done to determine if a variation in isotope ratio as a function of depth occurred. The data for each hole are presented on one graph as profiles of nitrate concentration with depth and profiles of δ value with depth.

The profile in Figure 16 shows the nitrate in soil beneath a barnyard. The nitrate concentrations are high and the δ values are high. There appears to be a dependence of δ value on nitrate concentration, but not on depth. Groundwater contaminated by nitrate from this site would exhibit a high δ value.

The profile in Figure 17 is located on a turn row of a cotton field. Nitrate is high, but the δ value is consistently low. According to what appears to be reliable historical data, no fertilizer has been used here and no cattle have grazed here. Earlier soil studies showed the chloride to be very low at this site (see hole 12 in Appendix III). Groundwater contaminated by nitrate from this site would exhibit a low δ value.

The profile in Figure 18 is also from a cotton field. The nitrate is fairly low and the δ value is low. No particular dependence of δ value on depth is apparent. Groundwater contaminated by nitrate from this site would have a low δ value.

The profile in Figure 19 is from a cultivated field where cattle have grazed after harvesting of the corn or sorghum normally grown there. The nitrate content is quite low, and in contrast to the other holes, there is a decided decrease in δ value with depth below 3 feet. Note that the nitrate concentration is relatively constant with depth. The most logical explanation for this is a "chromatographic" type separation due to selective adsorption of the heavier isotope. Alternatively, the deeper nitrate could represent nitrate formed before the area was settled, and the shallower nitrate could reflect the influence of cropping and grazing after the land was put into cultivation. The nitrate content is so low that only a few cows might exert considerable influence on the isotope ratio of the nitrate. As discussed earlier, the relationship between the depth of the nitrate and the "age" of the nitrate is not clear. A rising water table at this site would leach out nitrate with a fairly low δ value.

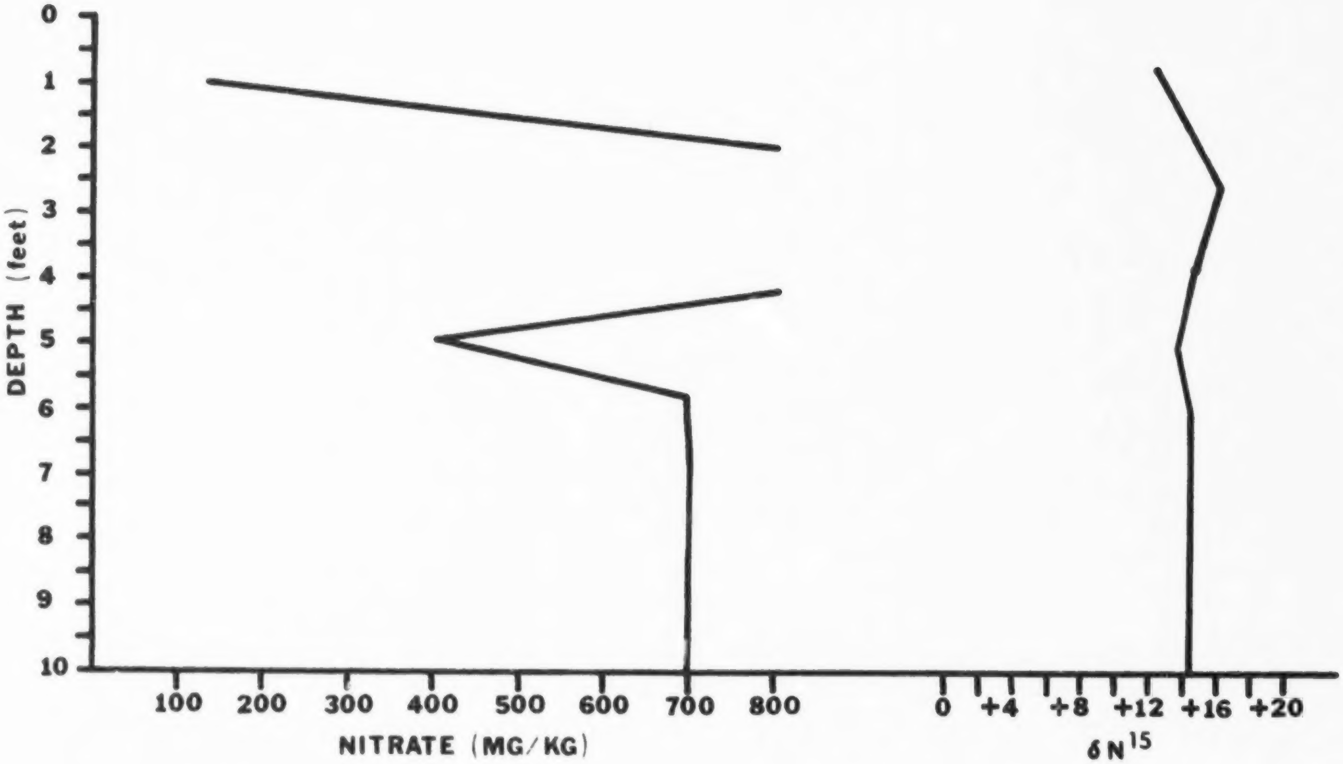


Figure 16. Isotope Ratio Profile with Depth for Barnyard

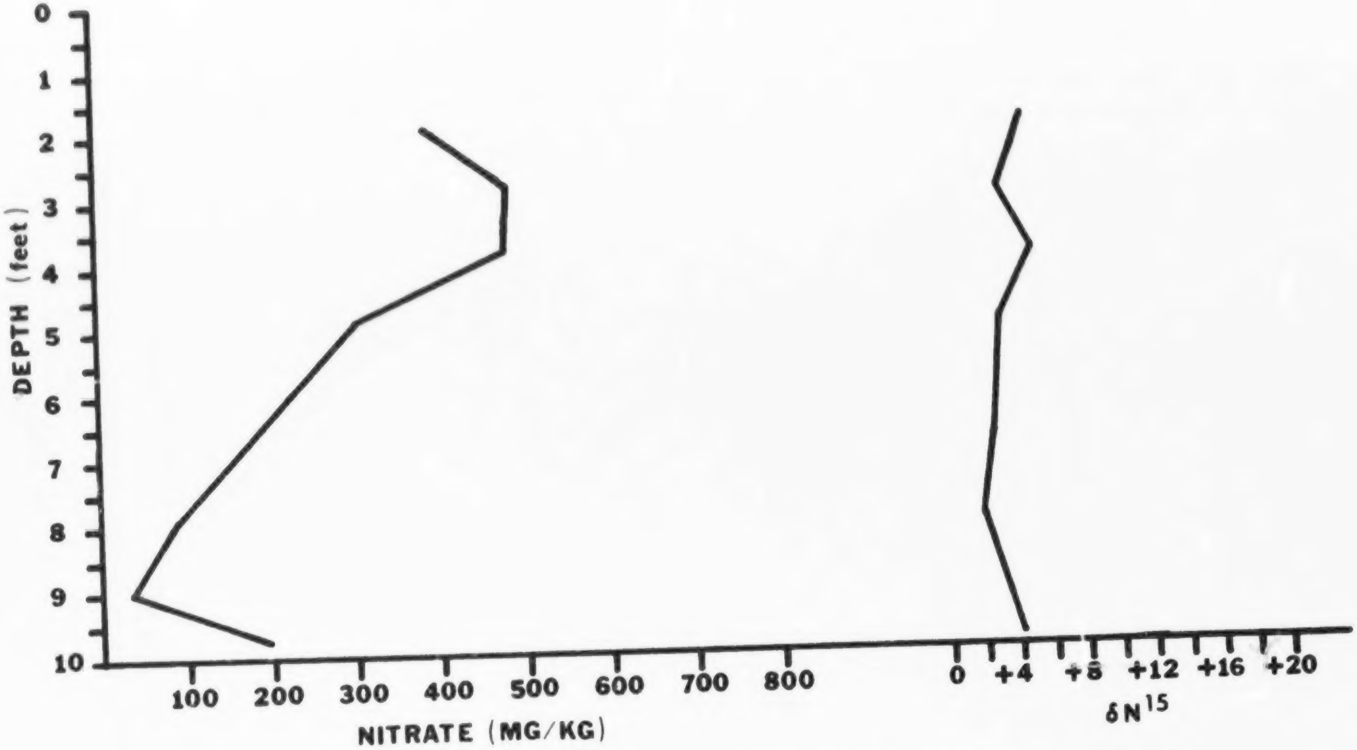


Figure 17. Isotope Ratio Profile with Depth for Cotton Field

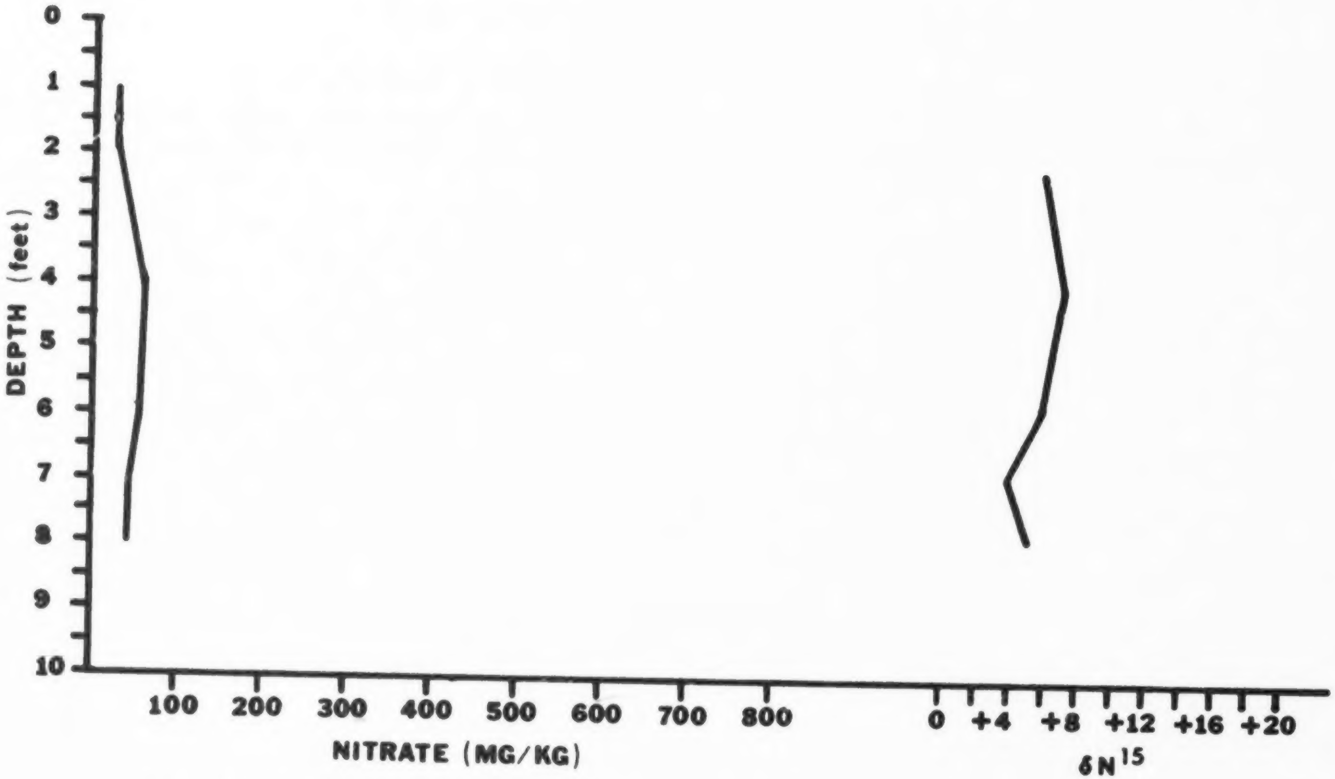


Figure 18. Isotope Ratio Profile with Depth for Cotton Field

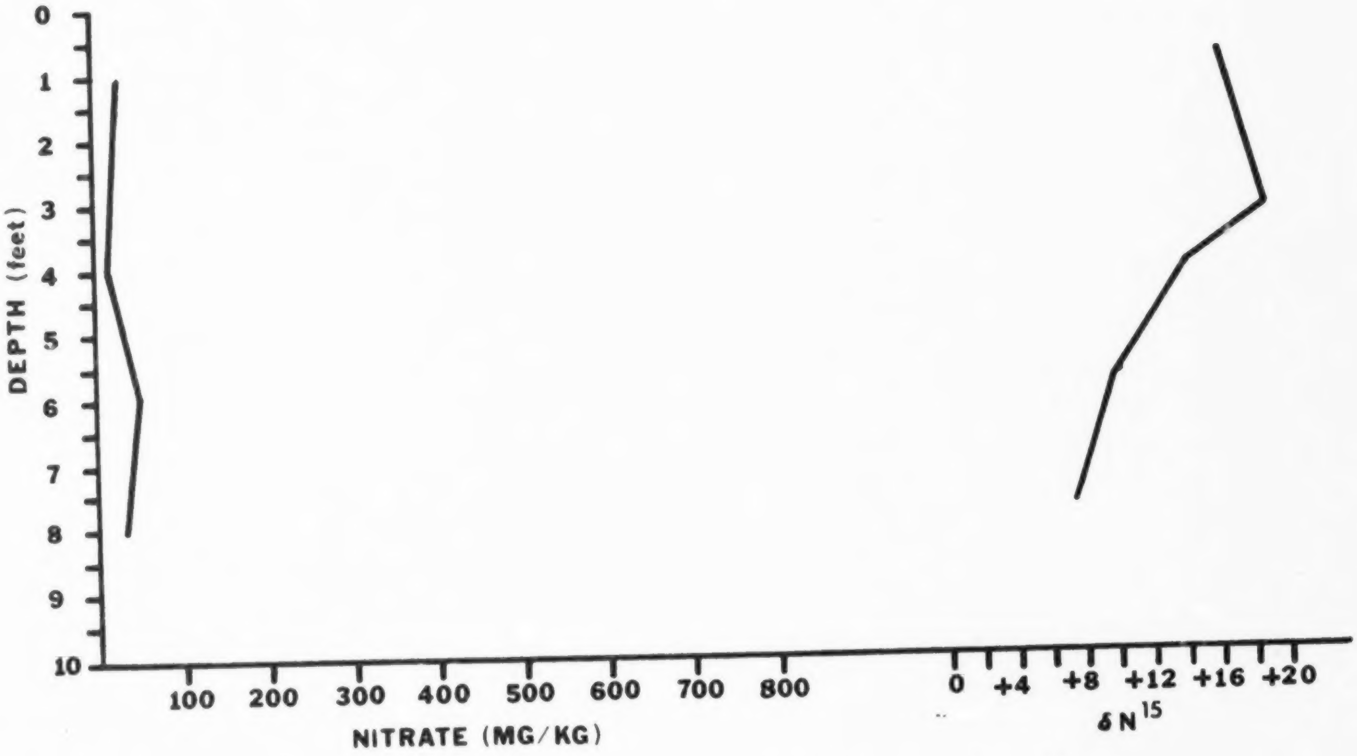


Figure 19. Isotope Ratio Profile with Depth for Cornfield

The profile in Figure 20 consists of only two data points because of sample preparation problems. The site was a maize field. The nitrate content is very low, but one of the two δ values obtained was fairly high. Possibly, cattle grazing on the stubble of the crop were able to contribute significantly to the small amount of nitrate which does occur. A rising water table at this site would initially encounter nitrate with a fairly low δ value.

Miscellaneous Samples

Fourteen barnyard soil samples were obtained. The δ values were as follows: +4.8, +12.4, +12.9, +13.3, +13.5, +13.6, +13.9, +14.0, +14.3, +14.6, +15.1, +15.9, +16.5, +21.9. No reason is apparent for the +4.8 sample. Possibly an anaerobic condition had developed and denitrification was occurring.

Five samples were obtained near septic tank laterals. These exhibited the following δ values: +10.2, +12.4, +10.3, +13.0, +17.8. There is some question about the 17.8 value since it was later discovered that this particular lateral crossed the site of an old hen house. It is interesting that Commoner[illegible] found the following δ values for nitrate in sewage: +11.5, +10.3, +14.5.

No fertilizer samples were run since this data is available from the literature. Kohl[illegible], et al., found the δ value for fertilizers to range from 0 to +4. It would be expected that ammonia formed by the Haber process would exhibit an isotope ratio similar to that of air because of the high temperatures involved. Subsequent reaction of this ammonia to form other types of nitrogen fertilizers could induce fractionation, however, if the reaction was done at low temperature and was not 100% complete.

Nitrate samples from pastures were not checked since cattle invariably grazed these areas, thus there was no way to get a nitrate sample which could be reasonably certain to represent only the background nitrate from sources other than cattle. The only nitrate sample which is believed to faithfully represent this background nitrate from a pasture is from a spring in a pasture (see well 301 in Table 10). (Since cattle typically gather around wells in pastures and the wells are poorly cased, and flow only occasionally, localized contamination is possible.) This spring had a δ value of +6.3, which agrees well with the δ value for background nitrate under fields where cattle had not grazed. (See Figures 17 and 18.)

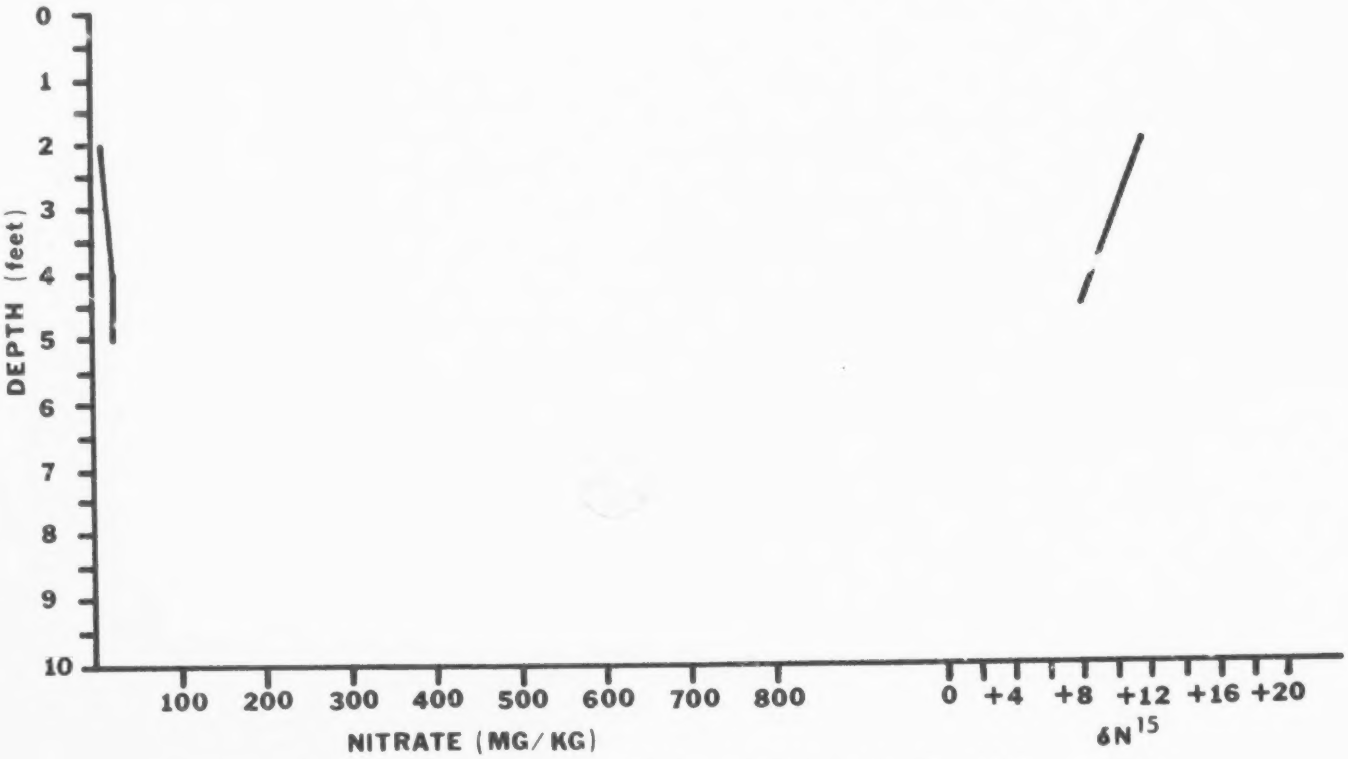


Figure 20. Isotope Ratio Profile with Depth for Maize Field

Discussion of Isotope Ratio Studies

It is interesting to plot the δ values for the water wells as a function of nitrate concentration as shown in Figure 21. With only a few exceptions, there seems to be a general trend of increasing δ value with increasing nitrate concentration. (Analysis of standards of different concentration showed that this trend was not a result of the sample preparation.) Such a tendency indicates that the nitrate is coming from at least two different sources, since if there were only one source, all the nitrate should have approximately the same δ value. The biggest exception is an irrigation well (No. 868). Although this well had only 21 ppm ($\delta = +13$) in 1972, it had 920 ppm in 1969. Possibly, extensive pumping of this well has altered the water table locally so that it no longer intersects bedded nitrates, and almost all the contaminated water has been removed by pumping. The very high 1969 nitrate level and the 1972 δ value would indicate animal wastes as the source of contamination.

In general, the results of the isotope study can be stated as follows. Nitrate from animal wastes will exhibit a δ value in the range of +12 to +17. Nitrate from human wastes will exhibit a δ value in the range of +10 to +14. Nitrate from soils where livestock have not grazed and fertilizer has not been used ranges from +2 to +7. As reported earlier, fertilizer ranges from 0 to +4.

Although there is some overlapping of these various δ value ranges from various sources, this is considered to be a very fortunate "spread" of δ values. Human and animal wastes are neatly segregated from soil nitrate, and this permits the very important distinction between contamination from localized sources such as barnyards or septic tanks and contamination from background sources such as soil nitrate. It is not nearly so important that a clearcut distinction cannot be drawn between contamination by human wastes versus contamination by animal wastes, since either one indicates poor well construction and/or a well too close to localized sources of nitrate.

It is noteworthy that the results of the isotope study reinforce one of the conclusions of the soil study, namely that nitrate with no associated chloride does not come from animal wastes.

One point is worth re-examining. As discussed previously, the source of the "background" nitrate in the soil is not

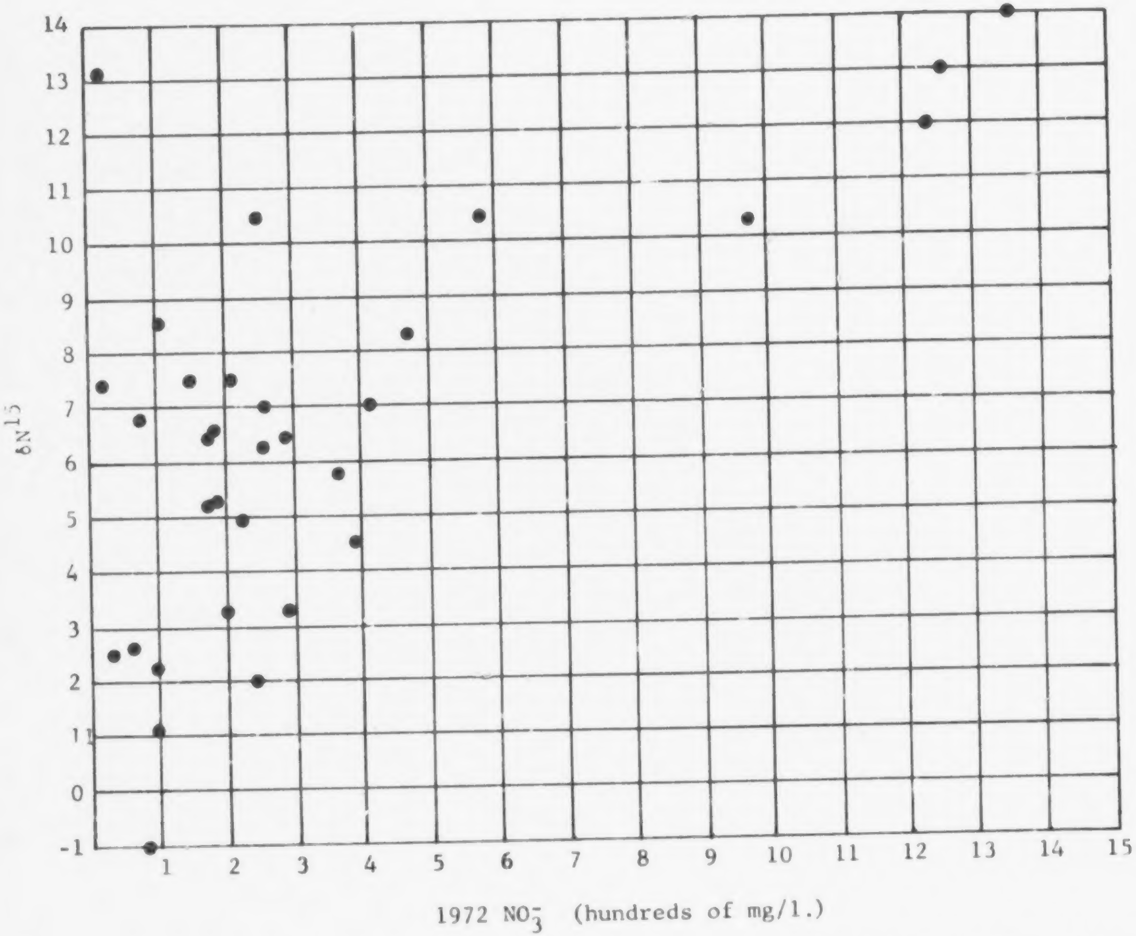


Figure 21. Isotope Ratio as a Function of Nitrate Concentration

clear. The most reasonable explanation is that this nitrate is a decay product of vegetation and has slowly accumulated beneath the root zone of plants over a period of many years (perhaps hundreds). Such a situation would require a rather unique set of climatic and geologic conditions. A less likely explanation for this nitrate is that it was an oxidation product of free-living nitrogen-fixing bacteria. Another unlikely explanation is that it is the oxidation product of nitrogen contained in sedimentary rocks. In any case, this nitrate appears to be naturally occurring, i.e., not due to the activities of man. The δ value indicates it also is not due to animals.

In light of the soil nitrate isotope studies it is worthwhile to re-examine the results of the groundwater isotope studies (see Table 10). Those wells with very high δ values (865, 868) would appear to derive the great majority of their nitrate from animal or human wastes. Those wells with high δ values (867, 1004, 1034, 388, 421, 551a) would appear to derive most of their nitrate from human or animal wastes but with some contribution from natural nitrate. Another group of wells have a δ value which is on the high end of the soil nitrate range but could represent a small contribution by human or animal wastes (67, 105, 144, 233, 369, 551, Rowena Municipal Supply). Still another group appears to be contaminated only by natural nitrate (15, 16, 18, 201, 234, 301, 309, 366, 386, 419, 506, 728, 1002, 1003). Two wells, 552 and 165, had δ values slightly lower than any observed during the study of soil nitrates. No explanation for these can be given at this time.

To summarize the results of the isotope studies, it appears that most of the nitrate contamination is due to natural nitrate. However, the extremely high nitrate wells all appeared to derive most of their contamination from animal or human wastes. (It was at these high nitrate wells that the great majority of cattle deaths occurred.)

It should be noted that only Runnels County soils were studied. It is not yet clear whether these results will have widespread applicability. It seems likely that they should at least apply to other areas of West Texas of similar climate, particularly on the Permian outcrop. The excellent agreement between the δ values obtained for nitrate from septic tanks in this study and Commoner's findings for nitrate from sewage are encouraging in this regard.

Infrared Photography Studies

No difference could be detected in the reflected infrared radiation from plants grown in low and high nitrate areas. Approximately 500 photographs were taken in Runnels County, but in no case could a clear cut difference be detected between plants in low and high nitrate areas. Both cotton plants and mesquite trees were included in the study.

There are several possible explanations for the lack of difference in infrared reflectance between plants grown in low and high nitrate areas. As mentioned earlier even the low nitrate areas in Runnels County contain a great deal of nitrate. Perhaps the plant becomes saturated with nitrate even in these zones and does not accumulate any additional nitrate even when exposed to much greater concentrations. In this case infrared photographs would not show a difference since plants in both areas would represent high nitrate cases.

Another possibility is that some difference actually exists between plants in low and high nitrate areas, but the camera-film-filter combinations used were not sensitive enough to detect it.

Still another possibility is that the plant types chosen for photography are not strongly sensitive to nitrate concentration in the soil. The mesquite trees and cotton were chosen because they are widely occurring and in the case of the mesquite has a very deep root system. Some other type of plant might provide a better index to nitrate however.

Methods for Obtaining Potable Water

Location of Uncontaminated Water

The fact that much of the soil nitrate is naturally occurring makes the location of uncontaminated water by drilling a new well an uncertain proposition. Prediction of high soil nitrate at sites such as barnyards and septic tanks is relatively easy; however the prediction of the site at which natural nitrate occurs is not. No area was found to be free of soil nitrate; thus, relocation of a well might lead to a reduction in nitrate but not an elimination of nitrate (and possibly an increase). In general, it was found that the area of a farm complex (house, barn, etc.) had considerably more soil nitrate than more remote areas. It could therefore be expected that drilling a new well at some distance from the farm complex would yield some improvement in water quality. In general, this is probably the case. In each case, however, it should be remembered that groundwater can move from one area to another, and this movement can be accelerated by the artificial gradient imposed by a pumping well. A new well should therefore be located up the natural gradient from the farm complex. (The groundwater gradient will usually follow the surface gradient, however, in limestone aquifers this may not be true.) Also, the well should not be pumped extensively in order to avoid large artificial gradients. In addition, the previous history of the land must be considered. Many sites of old farm complexes exist from the days when there was a different farm on every quarter section. The soil studies showed that very high soil nitrate may still exist at these sites. It would be undesirable to locate a new well near one of these sites. Proper completion of a new well (good casing which is cemented to exclude very shallow groundwater) could help assure better quality water.

To summarize, drilling a new well is an uncertain venture. Some improvement in water quality will likely be obtained, however, it is unlikely that the water will meet the Public Health Service limit of 45 ppm nitrate. One other point is noteworthy. Water from a new well might start out good but later turn bad due to encroachment of contaminated water. Water samples should be submitted for analysis on a regular basis.

Removal of Localized Contamination by Pumping

The major nitrate problem occurred when the rising water table dissolved soil nitrate. The water table has since receded in most areas, carrying the dissolved nitrate with it. If the major source of contamination is localized (e.g., a barnyard) it may be possible to pump out this contaminated water. The quality of the water will then be determined by the natural nitrate contained in the water which moves in laterally from surrounding areas due to the artificial gradient established by the pumping. This approach pre-supposes there is something to do with the contaminated water which is pumped out. One approach would be to divert it to some natural drainage channel such as a creek. However, depending on the water quality, this might violate some pollution statutes. Another approach might be to spray it on surrounding fields (irrigation). In theory the nitrate would eventually find its way back into the groundwater. In fact, the nitrate added to the soil would probably be small compared to the amount already in the soil above the water table. If this approach were adopted, the water should be spread over a large area. One reason for this is that the highly saline groundwater will deposit salt in the soil due to evaporation and this salt could hurt crop yields if too much accumulated. Another reason is that too much water applied in one spot might saturate the soil, resulting in rapid percolation of the nitrate-bearing water back into the groundwater.

It is not possible to predict how much pumping would be required. This would depend on the porosity and thickness of the aquifer and the extent of the contamination. Pumping costs could be considerable.

In general, this approach has the same limitation as drilling a new well, namely, the final water quality will be dictated by the amount of natural nitrate which was leached by the aprising water table in the surrounding area. This whole approach of pumping out the contaminated water depends on keeping the water table low in the future. There will still be much nitrate in the soil above the water table, and there is no economically feasible way to remove this nitrate. Any big rises in the water table must therefore be avoided.

Purification of Contaminated Water

Three points are noteworthy regarding purification of the groundwater. First, only enough water for actual consumption by human and animals is required. Well water can be used for other purposes. Secondly, most purification processes not only yield purified water but also yield in some sort of waste stream the contaminants which were removed from the purified water. Some provision for disposal of these wastes will be required. Third, it should be noted that nitrate-containing water cannot be purified by boiling. The concentration of nitrate will instead be increased due to loss of some of the water by evaporation.

Many processes have been developed for the removal of dissolved species from water. The most successful of these are the following:

(1) Distillation

(2) Ion Exchange

(3) Reverse Osmosis

(4) Electrodialysis

(5) Crystallization (Selective Freezing) Processes

For large water treating installations, each of these techniques has shown feasibility. Small units are available for some of these processes. In some cases, e.g., ion exchange, the cost of water purification is strongly dependent on the total quantity of dissolved ions in the water. None of these processes will selectively remove nitrate. Most of the processes will produce water which has had virtually all of the dissolved species removed. This water could be mixed with untreated water to yield a mixture with an acceptable concentration of dissolved species, thus increasing the amount of potable water available for a given cost of treated water. The economics of each of these processes will depend on the particular conditions, namely, the quantity of water required and the concentration of contaminants in the groundwater. It is unlikely that small (household-size) units for any of these processes will prove to be economically feasible in the great majority of cases.

An alternative approach to many small purification units would be to have a large central water treating system which distributed water to the various farms. Again, however, the capital investment in the treatment plant and distribution system would likely render this approach economically infeasible. It would likely be more economical to pipe in water which did not need treating (either surface water or groundwater) and put this into the distribution system.

One technique has been developed for the selective removal of nitrate from water. This technique makes use of the fact that certain bacteria will convert nitrate to nitrogen gas if no oxygen is present (anaerobic conditions) and if an energy source (usually organic carbon) is available. In practice, methyl alcohol is added to the water at a level such as to first remove all oxygen and then remove all nitrate. Since the nitrate is converted to a gas, no waste stream occurs. Large units of this type have been demonstrated. It is unlikely that small units would be economically feasible, however, due to the careful monitoring required for oxygen and nitrate and the accurate metering required for the methyl alcohol. Also, the high salinity of the groundwater in Runnels County might provide an unfavorable climate for the nitrate-reducing bacteria.

Another selective removal process might make use of aquatic plants to remove nitrate. In this case, groundwater could be pumped to a surface pond where plants grow. Nitrate is, of course, an excellent plant food; thus, rapid plant growth could occur. As a long term solution, however, periodic harvesting (and disposal) of these plants would be required since old plants would start returning nitrate to the water when they died. Such underwater harvesting probably would not be economically feasible on a small scale. Again, the high salinity of the groundwater could be detrimental to plant growth. Evaporation could greatly increase the salinity during hot, dry periods. In addition, the efficiency of this removal process might vary seasonally.

Cisterns

Collection of rainwater which drains off the roof of a building has long been a common practice in some areas of the country. Rainwater is relatively pure; however, contamination may be flushed off the roof and into the cistern. The best approach would be to divert the initial flow of rainwater away from the cistern and collect water after the roof had been washed off. In dry periods all available water might be needed, however. Proper screening of the system would be required to prevent birds, insects, and trash from getting into the cistern.

Several cisterns might be required to furnish water for both household needs and farm animals. Possibly the cisterns could be supplemented by hauling water during dry periods.

Again, it should be noted that uncontaminated water is only needed for consumption by humans and animals. Well water could be used for bathing, dishwashing, washing clothes, etc.

Surface Water

Rainwater runoff could be trapped to provide a water supply in some areas of the county. This requires damming some natural drainage channel and is already common practice through the county to provide "stock tanks". On land which is very flat or heavily terraced runoff may be negligible, however.

As mentioned earlier, rainwater typically contains only 1 ppm nitrate. During runoff, some additional nitrate would likely be picked up from the topsoil, but the final concentration should still be much less than the groundwater contains. Small chlorination units (which use a commercial bleaching agent) are available which automatically meter the proper quantity of chlorine into the water when the pump is on. This chlorine should remove bacteria, and a filter could remove suspended solids, thus providing a water supply of good quality. This approach is common for houses near large lakes.

It should be noted that such a pond acts as a recharge zone for the groundwater and, if the soil is porous, the water may quickly disappear due to percolation (and evaporation).

Percolated Surface Water

Alternatively, one might take advatnage of the natural "filtering" action of the soil when water percolates through it. In this approach, a well would be drilled adjacent to a stock tank. If the stock tank is old, the soil nitrate below that tank has most likely been removed due to dissolution in percolating water. A well adjacent to that tank which is pumped on a very limited basis (only enough to provide water for consumption) might provide water of good quality. It should be noted that fine-grained soils are best at removing bacteria and organic materials. Limestone formations have a very limited ability in this regard.

SECTION VI

ACKNOWLEDGEMENTS

This investigation was sponsored by the Texas Water Development Board and the Environmental Protection Agency. The work was performed by Radian Corporation, Austin, Texas. The Project Officer for the Environmental Protection Agency was Jack W. Keeley. The Project Officer for the Texas Water Development Board was Fred Osborne, and the Project Director for Radian Corporation was David [illegible]. Jones.

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SECTION IX

GLOSSARY

ml - milliliters

ppm - parts per million

mg/ℓ - milligrams per liter

gal - gallons

ft - foot

T.U. - tritium unit

Kg - kilogram

mg - milligram

# - pounds

δ - nitrogen isotope ratio

α - isotope equilibrium constant

SECTION X

APPENDICES

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APPENDIX I

RESULTS OF WATER SAMPLE ANALYSES

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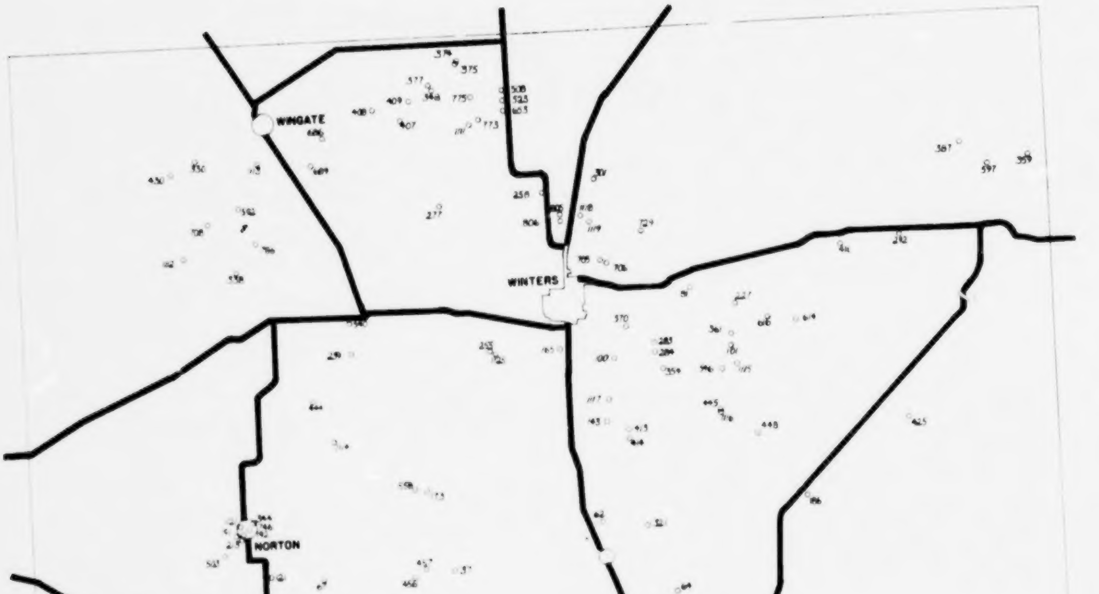
WINGATE
WINTERS
NORTON
BALLINGER
ROWENA
MILES
STUDY AREA

Figure 22. Water Well Location Map

All Analyses in Milligrams per Liter

Well No.	Owner	NO_3^-	1969 NO_3^-	TDS	1969 TDS	SiO_2	Ca^{++}	Mg^{++}	Na^+	HCO_3^-	$SO_4^=$	Cl^-	F^-
1	Emil Kloesil	204	60	3,630	2,400	16	660	175	223	234	1,810	420	3.5
5	L. F. Loika	242	300	1,590	1,470	22	265	33	230	296	210	443	.8
8	C. Schaefer	357	370	2,150	1,908	19	216	118	328	276	472	497	4.5
15	O. Steinback	340	280	2,080	3,000	22	211	109	339	257	387	630	2.6
16	O. Steinback	250	220	2,030	1,650	23	274	155	185	220	274	670	1.9
17	Alvin Halfman	410	280	1,730	1,680	24	232	89	197	343	216	388	1.7
18	Alvin Halfman	791	540	2,390	1,800	27	417	89	192	326	202	510	1.2
23	Roy Schaefer	357	270	1,600	1,050	27	186	43	287	260	125	445	1.1
27	L. Luedtke	90	85	1,140	1,020	23	131	72	164	250	145	387	1.2
33	Mrs. J. Kresta	220	185	2,110	1,800	29	307	45	354	290	422	590	1.9
37	Leon Gibson	171	200	1,580	1,800	21	208	62	245	221	199	560	1.3
45	A. Book	20	16	1,070	1,140	16	121	86	150	316	113	405	2.2
59	Mrs. Otto Halfman	420	340	1,870	1,680	19	210	91	270	282	256	458	2.2
62	H. Tierce	128	160	1,450	1,320	20	112	173	123	265	407	352	0.9
64	Bruce Howell	347	250	3,260	3,300	35	450	199	410	284	222	1,450	1.7
65	F. Gallas	184	135	1,370	1,560	20	173	120	121	326	203	386	1.7
67	Cone Robinson	288	330	1,260	1,200	I.S.	154	26	247	323	174	233	I.S.
75	N. Romfield	220	260	1,840	1,320	29	269	30	317	244	367	484	1.9
76	N. Romfield	150	140	1,100	1,680	20	88	43	225	151	211	284	1.9
81	J. C. Busher	130	105	960	900	21	178	37	94	238	89	293	0.4
83	C. H. Patton	120	90	1,090	450	30	107	59	182	351	168	248	2.5
84	C. H. Patton	230	225	1,860	1,560	34	252	97	246	251	268	610	2.0
85	C. H. Patton	110	115	1,160	1,020	25	131	80	158	322	141	352	---
98	L. Hoelscher	240	280	1,750	1,560	27	168	83	291	298	286	486	4.1

RESULTS OF WATER SAMPLE ANALYSES

All Analyses in Milligrams per Liter

Well No.	Owner	NO_3^-	1969 NO_3^-	TDS	1969 TDS	SiO_2	Ca^{++}	Mg^{++}	Na^+	HCO_3^-	$SO_4^=$	Cl^-	F^-
100	Gene Bowles	224	170	1,910	2,280	24	211	146	232	390	285	590	0.9
101	I. W. Rogers	110	90	1,360	1,020	23	202	64	188	277	160	474	0.6
105	W. V. Connelley	<.4	56	760	960	27	102	60	81	362	164	145	0.8
112	R. Bruchmiller	280	48	3,510	1,920	22	740	78	233	281	1,630	383	1.3
112	R. Bruchmiller	3,584		8,100		24	1,390	226	590	244	1,300	840	2.5
113	R. Bruchmiller	419		1,170		17	211	18	129	201	113	163	1.4
114	R. Bruchmiller	8.5		870		22	179	26	94	383	186	160	0.8
115	R. Bruchmiller	29	120	2,660	1,680	19	690	27	129	294	1,340	279	1.8
116	R. Bruchmiller	312	320	1,940	1,800	24	336	27	265	250	237	610	1.6
117	V. Glass	110	145	1,210	1,200	25	155	64	175	254	178	373	1.8
118	G. Schaefer	250	420	2,170	1,860	26	333	86	297	174	253	840	2.1
119	G. Schaefer	344		2,210		29	276	87	328	337	493	481	2.1
121	Steve Stubblefield	242	210	1,620	1,200	29	207	49	271	268	230	463	1.4
125	A. Wendland	36	32	500	510	24	72	42	50	325	30	87	1.2
126	G. Klaus	310	370	1,110	1,080	33	131	38	163	217	147	177	2.5
141	R. Hohensee	220	320	940	900	22	163	36	97	294	103	156	0.8
143	Walter Adami	180	170	1,620	1,560	22	161	98	265	304	213	530	1.1
147	Miss Agnes Hoelscher	210	185	2,040	1,800	21	232	134	273	237	358	700	0.9
148	C. Hoelscher	155	290	1,190	1,260	22	168	90	97	365	252	225	1.1
157	L. Frenzel	540	260	3,611	1,800	23	443	194	493	329	680	1,070	2.4
158	H. Halfman	405	340	2,140	1,560	22	266	111	302	338	245	620	1.7
162	J. Eggemeyer	3	26	1,780	1,080	20	211	103	213	266	980	120	1.9
164	P. Luedtke	80	95	1,190	1,140	25	161	71	158	270	126	432	1.3
165	Alvin Nitsche	326	490	2,600	2,400	22	189	175	472	383	401	820	4.6

RESULTS OF WATER SAMPLE ANALYSES

All Analyses in Milligrams per Liter

Well No.	Owner	NO_3^-	1969 NO_3^-	TDS	1969 TDS	SiO_2	Ca^{++}	Mg^{++}	Na^+	HCO_3^-	$SO_4^=$	Cl^-	F^-
173	Ralph Russell	243	200	1,030	840	20	140	25	153	232	162	173	0.7
177	A. Schwertner	34	36	750	660	34	89	42	113	423	139	87	1.9
182	Charles Moonen	809	480	3,950	2,280	16	615	287	162	276	1,510	413	2.1
186	E. E. Brown	27	22	1,130	960	22	129	95	140	390	205	319	1.6
191	Norton School	185	230	1,340	1.260	27	193	45	202	296	156	387	0.8
192	Leland Hilliard	90	55	930	960	20	143	35	129	265	145	237	1.2
200	A. Eggemeyer	65	85	1,150	900	24	171	71	137	290	120	415	1.5
201	H. Book	221	130	4,320	1,200	15	620	231	444	244	1,940	730	4.0
202	H. Book	90	12	1,320	264	24	175	67	195	264	205	429	1.7
204	W. Niehaus	378	350	2,300		16	252	134	348	234	458	690	2.8
205	W. Niehaus	284		2,380	2,400	19	193	159	399	287	331	750	4.8
210	V. Wallace	95	105	1,350	1,080	38	143	92	178	487	390	178	1.2
213	Inez Daniels	110	70	1,310	1,080	25	179	49	224	483	157	337	0.8
219	Juanita McIntyre	209	310	1,080	1,080	20	174	59	105	229	84	315	1.0
227	Lena Spill	80	80	860	960	22	114	73	84	357	99	213	0.8
228	W. Lange, Jr.	290	380	1,530	1,260	18	174	36	284	298	279	298	2.5
229	W. Lange, Jr.	357	240	1,330	1,260	20	187	30	202	287	184	202	2.3
230	W. Lange, Jr.	520	450		1,020	20	176	29	162	232	139	115	2.8
231	Mrs. J. Simicek	160	170	1,880	1,440	24	207	76	326	256	432	520	3.0
232	W. Lange	456	410	1,570	1,500	21	182	89	198	368	101	335	1.6
233	W. Beimer	572	600	1,560	1,380	35	142	57	286	279	241	279	3.1
234	W. Beimer	387	390	1,980	1,680	36	197	65	343	277	299	333	3.0
239	Tom Poe	187	230	850	1,020	21	117	25	127	260	91	147	1.8
251	P. J. Block	410	500	930	960	23	127	20	109	85	124	69	3.3

RESULTS OF WATER SAMPLE ANALYSES

All Analyses in Milligrams per Liter

Well No.	Owner	NO_3^-	1969 NO_3^-	TDS	1969 TDS	SiO_2	Ca^{++}	Mg^{++}	Na^+	HCO_3^-	$SO_4^{=}$	Cl^-	F^-
255	John Grohman	150	130	1,980	2,340	29	307	71	289	226	231	790	1.1
258	V. E. Colburn	420	330	2,250	2,160	24	264	134	294	216	233	770	1.9
264	C. L. Rogers	28	76	510	720	18	72	34	63	285	43	110	1.3
273	W. A. Namkin	294	48	2,470	1,680	19	389	115	283	281	471	760	1.8
277	Truett Smith	452	390	1,650	1,440	25	263	51	190	257	152	388	0.8
279	A. W. Hoelscher	351	440	2,410	2,400	20	268	135	355	323	328	790	2.8
283	M. E. Mathis	110	110	1,060	1,080	24	202	45	141	237	103	420	0.7
284	M. E. Mathis	31	45	850	960	23	145	35	107	232	82	306	0.8
285	G. G. Wiley	252	220	1,400	1,200	21	139	68	239	259	203	350	1.7
286	A. Schraer	100	155	1,490	1,320	23	163	78	235	265	287	395	1.9
288	Dan Woodruff	208	200	1,350	1,320	24	128	101	192	311	145	396	5.9
292	Charles Grohman	180	15	1,430	1,080	14	155	119	169	395	231	368	1.0
301	R. T. O'Dell	240	245	950	960	23	120	24	153	299	103	138	1.3
303	Mrs. Oscar Priem	336	320	1,320	1,320	23	102	45	255	303	216	195	1.6
309	Leila Harter	294	390	1,420	1,560	28	213	72	158	287	129	387	1.1
313	P. Halfman	777	660	3,710	2,880	25	500	162	486	227	373	1,270	3.3
314	P. Halfman	179		2,180		24	251	98	386	259	314	800	3.0
316	Gladys Davis	420	440	2,740	2,700	25	274	138	465	267	443	840	3.7
319	C. A. Gram	50	104	1,110	1,200	39	110	50	211	467	216	198	2.1
321	George Pruser, Jr.	170	200	1,110	900	20	69	88	182	375	197	192	3.4
324	F. J. Gulley	260	210	2,570	1,920	16	443	127	213	226	880	520	1.0
33	Severn O'Dell	11	13	2,630	1,800	16	415	170	150	92	1,760	60	1.3
338	J. B. Denson	384	250	1,280	960	22	226	60	97	289	52	296	0.7

RESULTS OF WATER SAMPLE ANALYSES

All Analyses in Milligrams per Liter

Well No.	Owner	NO_3^-	1969 NO_3^-	TDS	1969 TDS	SiO_2	Ca^{++}	Mg^{++}	Na^+	HCO_3^-	$SO_4^=$	Cl^-	F^-
344	Mrs. Roy Roper	190	190	1,220	1,150	25	175	43	174	251	151	329	0.7
348	Robert Conner	192	340	1,360	1,680	26	183	67	173	263	172	387	1.3
354	B. Phelps	110	88	1,030	1,140	22	167	37	118	272	117	314	0.6
359	R. B. Smith	3.5	3	560	600	15	94	21	79	431	84	43	1.5
361	Halley Schwartz	100	76	790	600	23	314	56	76	329	100	156	1.4
362	C. Henning	360	700	2,220	2,400	24	330	102	237	282	189	630	2.3
365	E. Kvapil	64	70	610	660	21	73	37	86	244	78	129	1.1
366	E. Kvapil	56	62	560	600	21	60	33	89	254	72	106	1.1
367	E. Kvapil	95	58	1,130	960	28	156	72	139	288	139	360	1.0
368	B. Ransbarger	130	115	1,800	1,440	44	139	27	413	339	397	436	2.4
369	B. Ransbarger	126	380	1,440	1,080	26	288	15	165	179	71	463	0.4
370	Wilma Davis	140	140	1,220	1,320	24	157	56	192	288	183	327	0.8
374	Omer Hill	210	185	1,410	1,500	19	209	28	155	270	172	429	1.1
375	Omer Hill	390	390	2,040	2,280	17	193	103	140	287	123	730	0.3
377	Robert Conner	215	250	1,280	1,680	26	178	60	163	282	168	327	1.4
379	D. Redman	225	205	960	900	23	83	27	191	259	165	115	3.2
385	B. Willberg	130	215	2,040	1,920	24	280	36	343	267	328	590	1.9
386	E. O. Eggemeyer	315	310	3,180	2,880	18	307	196	453	339	120	970	2.3
387	G. C. McGuffin	290	60	1,160	660	17	271	25	73	266	98	256	0.4
388	E. O. Eggemeyer	1,428	1,230	8,150		21	830	432	1,270	270	1,560	2,490	2.9
393	D. Ocker	168	170	1,310	1,680	20	180	62	173	268	276	296	0.7
394	C. Ocker	216		2,120		23	233	109	330	249	351	710	0.9
407	Barney Puckett	210	190	1,610	1,680	21	249	86	186	238	156	390	0.6
408	Barney Puckett	230	260	1,640	1,680	20	198	116	208	293	127	606	1.2

RESULTS OF WATER SAMPLE ANALYSES

All Analyses in Milligrams per Liter

Well No.	Owner	NO_3^-	1969 NO_3^-	TDS	1969 TDS	SiO_2	Ca^{++}	Mg^{++}	Na^+	HCO_3^-	$SO_4^=$	Cl^-	F^-
409	J. R. Woodfin	221	290	1,940	2,280	21	360	64	214	369	241	700	0.3
413	W. F. Phelps	132	130	2,930	1,480	20	320	159	520	299	236	1,370	1.3
414	W. F. Phelps	23	30	4,960	6,000	7	610	483	300	173	286	1,960	0.4
415	L. R. Pelzrl	1.5	4	1,630	1,200	16	182	118	245	243	394	690	2.1
416	Frank Laird	22	25	1,330	1,920	12	216	77	130	250	423	332	0.8
418	J. Busenlehner	190	230	1,140	1,080	20	207	24	138	232	131	265	0.5
419	J. Busenlehner	240	250	880	780	21	177	20	87	326	86	189	0.7
425	J. L. Shelton	160	190	1,080	1,020	17	119	35	199	312	180	211	2.0
430	Paul Michaelis	42	56	530	600	22	101	24	30	293	34	83	0.6
434	E. Moonen	12	35	3,600	2,700	36	229	240	660	600	1,340	780	3.1
444	Carl Gottschalk	364	380	1,360	1,440	23	234	64	115	438	116	207	0.6
445	Frank Carter	120	120	1,330	1,260	24	170	73	190	306	163	438	0.9
447	H. Schaefer	260	240	2,240	2,040	20	330	140	240	223	312	820	1.9
448	Mrs. Herman Spill	68	110	2,200	2,400	18	101	207	411	520	319	810	4.4
456	Joe Mueller	140	165	980	960	23	86	24	211	306	220	126	1.3
457	Joe Mueller	210	260	1,070	900	16	113	55	164	299	180	185	1.8
463	A. J. Glass	170	225	1,410	1,680	24	159	94	205	333	184	465	1.7
464	V. Schwertner	326	300	1,590	1,320	28	173	67	254	172	248	405	2.8
469	Harvey Gulley	288	155	1,460	2,400	23	165	45	282	282	259	278	4.7
471	T. Alverdo	80	50	3,460	2,700	18	530	220	286	273	1,670	520	2.3
473	A. Fuchs	336	860	2,040	2,470	24	354	93	304	196	920	344	3.4
475	Clarence Hallmark	<0.4	1	670	600	10	126	30	66 *	251	196	113	0.7
480	Ralph Russell	220	205	870	720	30	94	35	142	244	79	143	2.9
484	J. Haechten	336	350	1,620	1,680	22	236	67	193	210	249	410	2.5

RESULTS OF WATER SAMPLE ANALYSES

All Analyses in Milligrams per Liter

Well No.	Owner	NO_3^-	1969 NO_3^-	TDS	1969 TDS	SiO_2	Ca^{++}	Mg^{++}	Na^+	HCO_3^-	$SO_4^=$	Cl^-	F^-
493	Mrs. C. H. Midgley	200	300	2,260	2,280	24	234	148	317	439	680	439	2.1
494	W. J. Kahlig	809	810	6,120	3,600	19	650	309	970	287	1,060	2,070	3.3
495	W. J. Kahlig	1,365		4,970		19	670	226	580	259	690	1,290	2.5
496	A. Holubec	130	145	1,780	1,860	27	261	80	234	257	404	520	2.3
503	Travis Barrett	149	165	1 410	1,200	I.S.	194	52	231	217	239	442	I.S.
506	B. Wilde	221	190	1,370	1,260	18	226	41	179	288	198	343	0.9
508	Gene Virden	496	520	1,510	1,560	25	173	48	227	244	131	285	2.3
512	R. Lange	270	660	1,780	3,000	24	177	86	305	303	287	475	1.9
513	W. Urbanek	130	112	1,660	1,320	22	221	72	255	240	254	580	2.7
516	W. Urbanek	110	120	1,480	1,440	24	197	88	190	271	249	487	2.6
517	W. Urbanek	94		1,920		17	218	81	336	32	401	750	2.3
523	Willis Davis	304	462	910	1,080	26	144	28	100	246	75	107	1.2
540	C. W. Wessels	155	214	1,530	1,440	25	222	42	269	356	45	600	0.7
546	Bobby Rogers	6	12	1,240	1,080	21	184	104	81	365	530	136	1.1
551	P. Pieper	294	300	3,000	2,160	19	433	188	258	279	1,190	481	2.3
552	P. Pieper *Epm					*	32.3	9.5	15.1	3.4	7.2	15.4	
553	Harvey Gulley	290	290	3,280	960	14	570	182	213	272	1,370	510	2.1
558	Alfred Wessels	459	410	1,210	1,080	22	183	31	142	265	92	154	0.5
566	Duncan Hensley	200	230	870	900	22	119	51	94	251	65	198	1.3
567	Duncan Hensley	130	200	810	1,080	25	126	40	100	279	70	187	1.8
569	Henry Fowler	315	205	2,990	1,800	20	386	263	207	540	1,080	447	1.2
578	C. Matschek	10	18	7,000	4,320	18	1,010	322	1,020	300	1,390	3,100	1.0
591	L. R. Hancock	530	490	1,690	1,320	29	261	82	143	232	184	341	1.2

RESULTS OF WATER SAMPLE ANALYSES

All Analyses in Milligrams per Liter

Well No.	Owner	NO_3^-	1969 NO_3^-	TDS	1969 TDS	SiO_2	Ca^{++}	Mg^{++}	Na^+	HCO_3^-	$SO_4^=$	Cl^-	F^-
592	Jack Pritchard	85	680	780	1,440	24	128	28	107	275	60	213	0.6
597	Virgil Fuller	2	4	349	330	13	103	17	8	381	11	8	0.4
599	Miles Co-op Gin	180	175	1,230	1,140	21	133	68	202	311	111	355	3.2
600	A. Book	190	185	990	1,020	27	126	48	132	312	91	221	1.0
607	Wendell Lee	430	430	1,090	900	I.S.	115	46	155	207	125	116	I.S.
608	Fred Tidmore	504	510	1,700	1,560	21	142	66	301	331	245	255	0.6
614	Walter Gerhart	160	125	1.360	1 560	15	122	109	182	351	243	351	1.0
616	Walter Gerhart	180	80	1,130	1,500	25	113	76	150	333	288	132	1.1
626	F. Pohler	210	175	1,690	1,440	17	183	154	176	282	260	550	1.8
627	W. Wehlman	.4	10	2,610	1,680	20	413	198	123	310	1,470	230	2.2
630	R. Multer	270	220	2,010	1,260	20	215	125	291	267	312	640	0.8
638	Carlton Robinson	231	330	1,110	900	I.S.	216	30	118	178	71	350	1.0
653	Earl Dorsett	365	410	1,100	840	26	157	32	148	267	102	141	1.3
670	P. Frenzel	270	200	1,490	1,020	23	196	85	196	354	103	440	1.0
671	P. Frenzel	180	170	1,150	900	27	179	64	131	312	60	356	0.8
672	G. Ruppert	1,302	330	1,800	900	18	590	156	348	338	550	680	2.4
686	James Patton	120	245	890	510	25	111	33	145	222	99	248	0.8
689	James Patton	120	120	860	660	22	119	35	121	261	106	207	0.6
705	Ras Gideon	78	80	1,030	720	24	82	107	131	411	136	268	2.4
706	Ras Gideon	180	80	1,390	960	24	138	116	169	454	154	384	1.5
708	Mrs. C. R. Morrison	299	510	1,780	1,200	21	244	91	235	284	170	580	0.9
711	J. King	378	310	2,570	1,800	19	275	149	375	232	452	800	3.5
722	Marvin Patterson	351	290	1,040	660	35	127	52	118	255	91	141	3.8
727	J. Teplicek	1,620		5,400	20	850	325	333	354	1,080	980	2.9	

RESULTS OF WATER SAMPLE ANALYSES

All Analyses in Milligrams per Liter

Well No.	Owner	NO_3^-	1969 NO_3^-	TDS	1969 TDS	SiO_2	Ca^{++}	Mg^{++}	Na^+	HCO_3^-	$SO_4^=$	Cl^-	F^-
727	J. Teplicek	1,260		4,870		24	740	308	348	339	1,030	990	3.5
728	J. Teplicek	130		2,640		24	385	190	193	253	1,160	428	2.7
729	Albert Spill	130	68	1,320	780	21	265	48	114	171	160	496	0.4
746	Carl Lewis	100	290	980	1,440	I.S.	130	41	164	312	150	234	0.8
747	E. Urban	170	132	820	900	21	98	55	100	337	70	137	1.4
773	M. R. Williams	243	215	1,230	1,260	28	167	23	190	287	211	226	0.8
775	Mrs. A. T. Williams	296	255	1,310	1,212	17	152	34	230	237	209	249	0.7
784	A. Lange	300	170	2,380	2,010	21	336	178	223	227	326	880	0.8
786	E. F. Albro	324	300	1,150	1,080	24	154	73	109	310	102	209	0.6
805	V. D. Cooper	12	105	1,240	1,140	13	156	69	190	390	200	408	1.3
806	V. D. Cooper	<0.4	25	2,000	2,040	16	229	159	286	530	266	780	2.1
864	W. H. Dierscke	210	240	1,490	1,400	21	181	114	161	268	150	520	0.9
865	O. Halfman	1,660		4,780		21	770	108	540	242	472	1,090	2.2
865	O. Halfman	1,250		3,880		22	610	104	470	238	387	920	2.5
866	O. Halfman	200		2,010		27	165	80	413	389	416	510	2.3
867	O. Halfman	1,898		5,350		22	780	238	490	282	570	1,210	2.5
868	O. Halfman	920		4,100		20	700	95	530	166	396	1,350	2.5
869	O. Halfman	290		1,500	1,260	24	190	48	250	253	241	379	1.3
870	A. C. Wendland	110	310	640	780	24	98	47	52	320	57	89	1.1
1000	Smithwick	120		910		27	118	57	118	334	83	217	2.4
1001	J. Hohensee	190		2,150		12	300	93	272	283	920	351	2.2
1002	R. Schwertner	280		2,190		17	245	73	389	220	520	560	3.4
1003	E. Holobec	820		2,950		29	476	81	357	229	330	740	2.7
1004	Werner Lange	360		3,790		18	600	202	359	245	1,250	880	2.1

RESULTS OF WATER SAMPLE ANALYSES

All Analyses in Milligrams per Liter

Well No.	Owner	NO_3^-	1969 NO_3^-	TDS	1969 TDS	SiO_2	Ca^{++}	Mg^{++}	Na^+	HCO_3^-	$SO_4^=$	Cl^-	F^-
1008	J. Hohensee	59		331		23	64	9	24	168	13	5	0.3
1009	Arthur Halfman	112		1,350		25	175	65	205	265	208	430	1.8
1010	Cmereck	110		1,510		22	193	111	189	298	159	580	2.0
1032	J. Pfluger	25		3,130		18	620	118	235	285	1,380	590	1.0
1034	Mrs. F. Backhous	1,430	2,240	4,010	3,600	32	670	118	386	220	341	920	2.1
1034	Mrs. F. Backhous	2,162	2,240	4,980	3,600	30	840	142	412	198	328	970	2.3
1111	Jack Bishop	198	SNT	1,000		20	122	19	187	289	155	157	0.7
1112	Dewitt Bryan	165	SNT	1,550		22	210	69	239	254	172	550	0.7
1113	Valley Creek	28	SNT	540		8	72	34	77	275	79	102	0.7
1114	Valley Creek	26	SNT	472		11	67	16	82	156	50	143	0.4
1115	Bobby Rogers	130	SNT	1,300		22	172	73	167	303	232	349	0.8
1116	Frank Carter	100	SNT	1,290		23	160	76	186	299	167	429	0.9
1117	James Brown	210	SNT	1,850		23	214	128	242	273	197	700	0.9
1118	R. T. O'Dell	110	SNT	1,100		18	98	39	230	420	181	214	1.3
1119	R. T. O'Dell	23	SNT	730		15	81	28	142	339	123	148	1.0
1120	Dude Dunn	76	SNT	780		21	113	46	94	289	72	211	1.5
1121	Walter Niehaus	51	SNT	820		20	106	45	119	244	129	232	1.0
1125	John Grohman	15	SNT	2,220		6	276	96	402	84	281	1,100	1.3

RESULTS OF WATER SAMPLE ANALYSES

APPENDIX II

RESULTS OF WATER WELL INVENTORY

Well No.	Owner/Location	Depth of Well (ft.)	Depth to Water Table (ft.)	Depth to Water Stratum (ft.)	Well Lift	Well Type	Age of Well	Sewage Disposal Distance & Direction from Well	Barnyard Distance & Direction from Well	Nitrate Conc. (mg/ℓ)	Remarks
1	Emil Kloesil 2S Rowena	51 R			Electric	Plastic Cased	New	100Y SE		204	
2	Emil Kloesil 2S Rowena	37 R									
3	Emil Kloesil 2S Rowena	40-45 R	+.5 M								
5	L. F. Loika 7MS Ballinger	60 R		60, seep at 45	Electric	Cased	6 yrs.	50' E Cesspool		242	
6	C. Dankworth Rt.67, 2MS Ballinger			72	Electric	Cased		50' E	Next to water trough	886	Over-flowing septic tank
8	C. Schaefer 2½ SW Rowena	9.6 M	6 M		Wind	Cased	Old	150 Yds. N		357	
14	Ray Brown 1MS Ballinger	82 or 90 R	7½ M	28 50	Electric	Cased		40' S			
15	Otto A. Steinback 4S Rowena	62 R	50 R	44 54	Wind	Cased	Old			340	In the barnyard
16	Otto A. Steinback 4S Rowena	62 R		44 54	Electric	Cased		200' SW		250	
17	Alvin Halfman 4S Rowena W.	55 R			Electric	Cased	New	40' N	25' E	410	
18	Alvin Halfman 4S Rowena	55 M	27 M		Wind	Cased	Old		1' E of Barnyard	791	Right next to barnyard
23	Roy Schaefer 3MS Norton	47 M	14 M		Electric	Cased	Old	46' S		357	

RESULTS OF WATER WELL INVENTORY

Well No.	Owner/Location	Depth of Well (ft.)	Depth to Water Table (ft.)	Depth to Water Stratum (ft.)	Well Lift	Well Type	Age of Well	Sewage Disposal Distance & Direction from Well	Barnyard Distance & Direction from Well	Nitrate Conc. (mg/ℓ)	Remarks
26	Baker & Carwile 6S Ballinger	119 R		90	Wind	Cased	Old	¼M E			
27	Leonard Luedtke 3M NE Miles	70-75 R			Wind	Cased	Old	250Y S		90	
33	Mrs. J. L. Kresta 1M N Bethel	125 R	35 R	90	Electric	Cased		½M W	200Y W	220	
37	Leon Gibson 10M NW Ballinger	49M	33 M		Windmill	Cased	Old	100' N40°E		171	
44	Alfon Book 2¼M E Miles	47 R	16.5 M	47	Wind	Cased	Old				
45	A. F. Book son 2M N Miles	70 R			Electric	Plastic Casing	New	200' W		20	
59	Mrs. Otto Halfman 9 SE Rowena	50 M	28.6		Wind	Cased	Old	¼ M W 100 yds. E		420	Near deserted house
60	L. S. Cape 1M S Ballinger	27 R		18	Electric	Cased	New	100' W			
62	H. Tierce 1.5M NE Hatchel	60 R	50 R	60	Electric Pump	Cased	Old	110' S75° E		128	30 cattle grazed nearby
64	Bruce Howell 3M SE Hatchel	60 R	19 R	19	Windmill	Cased	Old	200' N15° W		347	Grazed cattle for a while
65	Freddy Gallas 3SE Rowena	60 R		20 50 Strongest	Electric	Cased	3 yrs.	300' NW		184	
66	Freddy Gallas 3SE Rowena	60 M	7 M								

RESULTS OF WATER WELL INVENTORY

Well	Owner/Location	Depth of Well (ft.)	Depth to Water Table (ft.)	Depth to Water Stratum (ft.)	Well Lift	Well Type	Age of Well	Sewage Disposal Distance & Direction from Well	Barnyard Distance & Direction from Well	Nitrate Conc. (mg/l)	Remarks
67	Cone Robinson 12M NW Ballinger	67 M	8 M	67	Electric pump	Cased	Old	30' E	70' SE (Chicken Houses)	288	50 cattle grazed nearby; 7000 chickens
71	Erwin Halfman 5M SW Ballinger							60' N		142	
71	Erwin Halfman 5M SW Ballinger	22.6 M	17.5 M			Dug					
74	Joe Hovarak River Rd., S Ballinger	40-50 R		40-50				100' SW			
75	Nobert Rohmfield 5S Ballinger	30 R	9 M	12-15 30	Electric	Cased		20' Cesspool	70' S	220	
76	Nobert Rohmfield 5S Ballinger							70' Cesspool	50' NW	150	Stock pond
81	J. C. Busher 4.5M E Winters	60 R			Electric pump	Cased	26 yrs.	80' N		130	Formerly disposed of cattle manure in east pasture
83	C. H. Patton 8M NW Ballinger	22 R			Windmill	Cased	Old	360' S60° E		120	
84	C. H. Patton 8M NW Ballinger	28R			Windmill	Cased	Old	*		230	*Over ½ mile from any house
85	C. H. Patton 8M NW Ballinger	30 R			Windmill	Cased	Old	*		110	*Over ½ mile from any house
98	Leoran Hoelscher 6S Ballinger	21 M	0 M	15	Electric	Plastic Casing	New		200' E 200' N	240	Well next to stock pond
100	Gene Bowles 5M SE Winters	50 R			Windmill	Cased	Old	100' S20° E		224	8-10 cattle grazed nearby

RESULTS OF WATER WELL INVENTORY

Well No.	Owner/Location	Depth of Well (ft.)	Depth to Water Table (ft.)	Depth to Water Stratum (ft.)	Well Lift	Well Type	Age of Well	Sewage Disposal Distance & Direction from Well	Barnyard Distance & Direction from Well	Nitrate Conc. (mg/ℓ)	Remarks
101	I. W. Rogers 5M SE Winters	33 M	17 M	30	Windmill	Cased	Old	66' E 75' N 50° E		110	
105	W. V. Connelley River Rd., S. Ballinger	13.1 M	4.5 M	13	Electric	Dug	Old	200Y N up the hill		<.4	
112	R. Bruchmiller 5M S Ballinger	90 M	37 M		Wind	Tin Casing	Old	40' N	10'	280	1st NO_3 test showed 3680 mg/ℓ
113	R. Bruchmiller 9M S Ballinger	12 M	1.5 M	≈12	Wind	Cased	New	½M E farm		419	
114	R. Bruchmiller 9M S Ballinger		60.5 M		Wind	Cased	Old	Deserted farm ½M W		8.5	
114a	R. Bruchmiller 9M S Ballinger	95 M	42.6 M			Cased	Old	20' W of house			
115	R. Bruchmiller 9M S Ballinger	65 M	32.7 M	62	Wind	Cased	Old	100' N		29	
116	R. Bruchmiller 9M S Ballinger	60 M	14.2 M	37	Wind	Cased	Old	½M N		312	
117	Vernon Glass 1M N Lowake	60-65 R			Wind	Cased	Old	100' E	105' E	110	
118	George Schaefer 1M W Martins Inn	60 R			Electric	Cased		40' S		250	House well
119	George Schaefer 1M W Martins Inn	73 M	19 M		Electric	Cased	New	250Y E		344	Irrigation well
121	Steve Stubblefield 1.5M S Norton	50 M	8.6 M		Electric Pump	Cased	Old	*		242	*Seep tank between well and house; cattle graze near well

RESULTS OF WATER WELL INVENTORY

Well No.	Owner/Location	Depth of Well (ft.)	Depth to Water Table (ft.)	Depth to Water Stratum (ft.)	Well Lift	Well Type	Age of Well	Sewage Disposal Distance & Direction from Well	Barnyard Distance & Direction from Well	Nitrate Conc. (mg/l)	Remarks
125	A. C. Wendland 4M W Miles	92 R							100' NW	36	House well
126	Gus Klaus 9M SW Ballinger	16.3 M	8.5 M	16	Electric	Dug		200' W	200' W	311	
132	A. W. Strube 1M E Rowena	100 R			Wind	Cased	Old	1/3M E	1/3M E		
141	Roudie Hohensee 4M N Miles	70-80 R			Wind	Tin Casing		House 20' to the S	20'S	220	
143	Walter Adami 5M SE Winters	40 R			Electric Pump	Cased	Old	70' S 70° W		180	
147	Miss Agnes Hoelscher 3M E Rowena	40 R						1/3M W	1/3M W	210	
148	Charles Hoelscher 3M E Rowena	60 R			Electric	Cased		40' S		155	
157	L. Frenzel 2M S Rowena	52.7 M	11.6 M		Wind	Cased	Old 35	150Y W	150Y W	540	
158	Harry Halfman S Olfen	54.7 M	27.8 M		Electric	Cased			30' N	405	
162	James Eggemeyer 1.5M N Miles	119 R		86	Wind	Cased		100Y E		3.0	
164	Paul Luedtke 3M NW Lowake	75 R		33				200Y S		80	
165	Alvin Nitsche 1M S Winters	11 R	4 R		Electric Pump	Dug	Old	96' S 10° W		326	Open cesspool 200' east

RESULTS OF WATER WELL INVENTORY

Well No.	Owner/Location	Depth of Well (ft.)	Depth to Water Table (ft.)	Depth to Water Stratum (ft.)	Well Lift	Well Type	Age of Well	Sewage Disposal Distance & Direction from Well	Barnyard Distance & Direction from Well	Nitrate Conc. (mg/ℓ)	Remarks
173	Ralph Russell 7.5M NW Ballinger	60 R			Windmill	Cased	Old	½M W		243	
177	Alex Schwertner 1M S Ballinger	38 R			Electric	Cased	New	60' SE	300Y W	34	
182	Charles Moonen 2M W Ballinger	24 R			Windmill	Cased	Old	130' N 5° E	100' N 70° W	809	Has a few cattle, hogs
186	E. E. Brown 12M NE Ballinger	40 R			Electric Pump	Cased	Old	600' N 30° E		27	85-100 cattle grazed
191	Norton School Norton	65 M	24.7 M		Electric Pump	Cased	Old	66' N 55° E 80' N 45° W 36' E		185	
192	Leland Hilliard Norton	53 M	25.2 M		Electric Pump	Cased	Old	32' S 45° W		90	
200	Arthur Eggemeyer 4½M SE Miles	66 R	47 R	35 57	Electric	Plastic Casing	New	200'	100'N	64	New well with packers above producing horizon
201	Herbert Book 1M NW Lowake	45+R		45	Electric	Cased		50' W	Barn 50' N	220	
202	Herbert Book S of Schwertner's	20 M	0 M		Wind	Dug	Old		½M W	90	Dug well next to stock tank
204	Werner Niehaus 6M S Ballinger	30 M	0 M	19	Wind	Cased	Old	1000' N 500' E	1000' N	378	
205	Werner Niehaus 6M S Ballinger	45 M	1.5 M	19 41		Plastic Cased	New	30' S of Well #204		284	

RESULTS OF WATER WELL INVENTORY

Well No.	Owner/Location	Depth of Well (ft.)	Depth to Water Table (ft.)	Depth to Water Stratum (ft.)	Well Lift	Well Type	Age of Well	Sewage Disposal Distance & Direction from Well	Barnyard Distance & Direction from Well	Nitrate Conc. (mg/l)	Remarks
210	Vernen Wallace S Ballinger	28	9		Electric	Dug		90' S 70' S		95	Well dug in gravels
213	Inez Daniels Norton	60 R			Windmill	Cased	Old	50' N		110	
219	Juanita McIntyre Wingate	80 R			Electric Pump	Cased	4 yrs.	30' W		290	
221	Robert Lee Jones S Ballinger			65 R				75' SW			
223	Walter Lange, Sr 9M S Ballinger	31 R			Electric	Cased	Old	25' N Cesspool		456	
227	Lena Spill 7M SE Winters	33 M	14.5 M	50	Windmill	Dug	Old	70' S 70° E	100' N	80	30-40 cattle
228	Walter O. Lange, Jr. 9M S Ballinger	60 M	16.8 M	30 60	Wind	Dug	Old	150' N		290	
229	Walter O. Lange, Jr. 9M S Ballinger-	32 R			Electric	Cased		25'		357	
230	Walter O. Lange, Jr. 9M S Ballinger	70 R			Electric	Cased	New	½M N			
231	Mrs. John Simecek 5M SW Rowena	45 R			Electric	Dug				160	
232	Walter Lange, Sr. 9M S Ballinger	28.6 M	14.2 M	25-28	Wind	Dug	Old				
233	W. Beimer 10M W Ballinger	29.16 M	14.31 M	25-28	Wind	Cased	Old 50 yrs.	30'N	40'S	572	

RESULTS OF WATER WELL INVENTORY

Well No.	Owner/Location	Depth of Well (ft.)	Depth to Water Table (ft.)	Depth to Water Stratum (ft.)	Well Lift	Well Type	Age of Well	Sewage Disposal Distance & Direction from Well	Barnyard Distance & Direction from Well	Nitrate Conc. (mg/ℓ)	Remarks
234	W. Beimer 10M W Ballinger	17.7 M	12.16 M	14-18	Electric	Dug	20 yrs.	50' NW	80' SW	378	
239	Tom Poe 6M W Winters	38 R	28 R		Electric Pump	Cased	Old	100' NE*		187	*Deserted farm house
251	P. J. Block N of Olfen	33 M	7.25 M		Wind	Cased	Old	1500' N 200' W		410	
255	John Grohman 3.5M SW Winters	24 M	12 M		Electric Pump	Dug	Old	70' S 80° E*	200' NE	150	*Cesspool; large feedlot upstream; 30 hogs, cattle grazed nearby
258	V. E. Colburn 5M NW Winters	22 M	8 M		Electric Pump	Dug	Old	46' S 60' S 20° E		420	Weak well
264	C. L. Rogers Wingate	90 R			Electric Pump	Cased	Old	400' S 60° W		28	
273	W. H. Namkin 7½ M SE Rowena	61 R			Wind	Cased	Old	75' S		294	
277	Truett Smith 7M NW Winters	22 M	8 M		Electric Pump	Dug	Old	200' NW		452	
279	A. W. Hoelscher 6M SW Ballinger	18 M	1 M	12	Wind	Dug	Old		300Y NW hog pen	351	
283	M. E. Mathis 3.5M SE Winters	36 R	19 R		Electric Pump	Casing	New	80' N 50° E 80' N 40° W		110	
284	M. E. Mathis 3.5M SE Winters	36 R			Windmill	Casing	Old	300' N 30° W		33	

RESULTS OF WATER WELL INVENTORY

Well No.	Owner/Location	Depth of Well (ft.)	Depth to Water Table (ft.)	Depth to Water Stratum (ft.)	Well Lift	Well Type	Age of Well	Sewage Disposal Distance & Direction from Well	Barnyard Distance & Direction from Well	Nitrate Conc. (mg/l)	Remarks
285	G. G. Wiley 2M W Ballinger	50 R			Electric Pump	Casing	Old	82' S 75° W		252	50 cattle grazed nearby
286	Arnold Schraer 1M N Lowake	55 R	20-25 R		Wind	Cased	100 yr.	70' N	100' SW	180	
288	Dan Woodruff 6M W Ballinger	33 R	30 R	30	Electric Pump	Casing	Old	300' N		208	
292	Charles Grohman 10.5M NE Winters	54 R	18 R		Electric Pump	Casing	Old	450' N 20° W		180	
301	R. T. O'Dell 4.5M N Winters	Spring		0				100' W		240	Estimated discharge ~25 gal/minute
303	Mrs. Oscar Priem 2M W Valley View	23 M	10 M	10	Windmill	Dug	Old	'M S		336	
309	Leila Harter Wingate	33 M			Electric Pump	Cased	Old	30' N 40° E		294	
313	Paul Halfman 11M SW Ballinger	34 M	6 M	10 25	Electric	Dug	Old	10' N		777	Dug well by the septic tank
314	Paul Halfman 11M SW Ballinger	37.15 M	5.0 M		Wind	Cased	Old	200Y N		179	Windmill in field
316	Gladys Davis 6M S Ballinger	40-45 R	5.91 M		Electric	Plastic Casing	Recased	50' S	½M W of hog pens	420	
319	C. A. Cram Rt. 67, 2M S Ballinger	17 M	10 M	15-17	Wind	Dug	Old	50' and 60'		50	
321	George Pruser, Jr. 2M NE Hatchel	70 R			Electric Pump	Cased	New	100' S 60° E		170	Raised cattle 5 years ago

RESULTS OF WATER WELL INVENTORY

Well No.	Owner/Location	Depth of Well (ft.)	Depth to Water Table (ft.)	Depth to Water Stratum (ft.)	Well Lift	Well Type	Age of Well	Sewage Disposal Distance & Direction from Well	Barnyard Distance & Direction from Well	Nitrate Conc. (mg/l)	Remarks
324	Frank J. Gulley 2M E Rowena	62 M	44.5 M		Electric	Cased	New pump & casing	50' E	In the middle of the farmyard	260	
325	Frank J. Gulley 2M E Rowena	80 M	35 M		Wind	Cased	Old				
330	Severn O'Dell 2M NW Wingate	50 R		50	Electric Pump	Cased	New	40' N 70' N 30° E		11	
338	J. B. Denson Wilmeth	50 M	16 M		Electric Pump	Cased	Old	66' N 25° E*		384	*Open cesspool until one yr. ago
344	Mrs. Roy Roper Norton	40 R			Electric Pump	Cased	Old	20' N 30° E		190	
348	Robert Conner 10M NW Winters	28 M	7 M	25	Electric Pump	Dug	Old	150' N 20° W		192	Some cattle grazed nearby
354	B. Phelps 5M E Winters	53 M	14 M	43	Electric Pump	Cased	Old	65' S 60° W		110	Raised some cattle 10-12 years ago
359	R. B. Smith 6M NE Crews	40 R			Electric Pump	Cased	New	*		3.5	*No house within ½ mile
361	Halley Schwartz 5.5M E Winters	40 M	11.5 M	19	Electric Pump	Cased	Old	100' SE *20' W		100	*Cesspool
362	Clarence Henning 2M S Rowena	70 M	10.3 M		Wind	Cased	Old	40' E	40' S	560	
365	E. L. Kvapil 1M E Miles	75 R		75	Electric	Cased		50' S	100' S	64	House Well
366	E. L. Kvapil 1M E Miles	75 R		75	Wind	Cased	Old	150' N	30' E	56	Windmill

RESULTS OF WATER WELL INVENTORY

Well No.	Owner/Location	Depth of Well (ft.)	Depth to Water Table (ft.)	Depth to Water Stratum (ft.)	Well Lift	Well Type	Age of Well	Sewage Disposal Distance & Direction from Well	Barnyard Distance & Direction from Well	Nitrate Conc. (mg/ℓ)	Remarks
367	E. L. Kvapil 1 M E Miles	75 R		75	Electric	Plastic Casing	New	100' N		95	Son's well
368	B. Ransbarger 17M SE Ballinger	74 M	24 M		Electric	Cased	Old	100' E	150' SE	150	House well
369	B. Ransbarger 17M SE Ballinger	52 M	22 M		Wind	Cased	±20 yrs.	½M W	20' N	326	
370	Wilma Davis 2M E Winters	57 R	37 R	47	Electric Pump	Cased	Old	80' S10° W		140	
374	Omer Hill 10M NW Winters	30 R	10 R		Electric Pump	Dug	Old	300' S 25° W	200' W	210	
375	Omer Hill 10M NW Winters	18 R	6 R		Electric Pump	Dug	Old	300' SE	In Stock-pen	390	
377	Robert Conner 10M NW Winters	100 R		28 36	Electric Pump	Cased	Old	100' N 20° W		215	
379	Daniel Redman 4M W Rowena	100 R			Wind	Cased	Old	200' W		225	
385	Ben Willberg 3M SE Rowena	85 R	≈45 R	60	Wind	Cased		100' W		130	
386	E. O. Eggemeyer 9M S Ballinger	43 M	20.75 M		Electric	Cased		200Y SE of house		315	
387	G. C. McGuffin 6M N Crews	60 R	30 R		Windmill	Cased	Old	*		290	*Moving outhouse; 30 cattle grazing nearby
388	Emit O. Eggemeyer 9M S Ballinger	80 M	6.95 M		Wind	Cased	Old	25' W	0' next to hogs	1428	Well next to hog pen. A few cattle died from the well water.

RESULTS OF WATER WELL INVENTORY

Well No.	Owner/Location	Depth of Well (ft.)	Depth to Water Table (ft.)	Depth to Water Stratum (ft.)	Well Lift	Well Type	Age of Well	Sewage Disposal Distance & Direction from Well	Barnyard Distance & Direction from Well	Nitrate Conc. (mg/ℓ)	Remarks
393	David Ocker 4M S Ballinger	37 M	27 M		Electric	Dug	Old	30' N		168	
394	Charles Ocker 4M S Ballinger	47 M	25.5 M		Wind	Cased	Old			216	Well located in corral
395	Ray Holtman 4M SW Ballinger	60 R			Wind	Cased		200Y N			
407	Barney Puckett 10M NW Winters	45 M	16.3 M		Electric Pump	Dug	Old	50' S 50° E		210	
408	Barney Puckett 10M NW Winters	25 R	12 R		Windmill	Dug	Old	*	**	230	*Located in middle of pasture; **30 cattle/year graze around well
409	J. R. Woodfin 10M NW Winters	60 R			Electric Pump	Cased	Old	60' S 10° E		221	Raised 30 cattle/year years ago
413	W. F. Phelps 6M SE Winters	35 R	20 R		Windmill	Cased	Old	188' W		132	Salt water pollution from oil well activity
414	W. F. Phelps 6M SE Winters	35 R			Windmill	Cased	Old	*20' N		23	*Outhouse; house has been deserted for years; salt water pollution.
415	Lee Roy Pelzrl 1½M N Miles	105 R			Electric	Cased	Old	70' SW		1.5	
416	Frank Laird 8M E Winters	16 M	0	12	Electric Pump	Dug	Old	250' S 70° E		22	20 cattle/year grazing nearby

RESULTS OF WATER WELL INVENTORY

Well No.	Owner/Location	Depth of Well (ft.)	Depth to Water Table (ft.)	Depth to Water Stratum (ft.)	Well Lift	Well Type	Age of Well	Sewage Disposal Distance & Direction from Well	Barnyard Distance & Direction from Well	Nitrate Conc. (mg/ℓ)	Remarks
418	J. Busenlehner 12M S Ballinger	40 R		28	Electric	Cased	New	½M W House		190	Irrigation well
419	J. Busenlehner 12M S Ballinger	60 R		35	Electric	Cased	New	30' W	200' S of pens	240	House well
420	J. Busenlehner 12M S Ballinger	18 M	13.6 M			Plastic Casing	New				Unused well
425	J. L. Shelton 2M S Crews	90+M	7.2 M		Drawn	Cased	Old	45' E		160	30 cattle/year grazing nearby
430	Paul Michaelis 3M NW Wingate	80 R		40	Electric Pump	Cased	New	1/3M E	50' W	42	100-150 cattle grazed on land
434	Ed Moonen 1M S Ballinger, Rt.83	34 R			Electric	Cased	New	½M N	½M N	12	by Colorado River
444	Carl Gottshack 10M SW Winters	18 M	10 M	10	Electric Pump	Dug	15 yrs.	200' SW	*200' W	384	*Used to be a 30 cow dairy
445	Frank Carter 6.5M SE Winters	30 M	13.3 M	20	Electric Pump	Dug	Old	80' S 70° W	100' E	120	
447	Hilmer Schaefer 2SE Rowena	63 R	25 M	50-55	Electric	Cased	10 yrs.	200' E	200' E	260	
448	Mrs. Herman Spill 8M SE Winters	12 M	8.3 M		Electric Pump	Dug	New	*	**	68	*Well located across a creek; **30 cattle/year grazed near well
456	Joe Mueller 12M NW Ballinger	50 R		30	Electric Pump	Cased	New	120' S		140	20 cattle/year grazed
457	Joe Mueller 12M NW Ballinger	21 M	16.5 M		Windmill	Cased	Old	300' NE		210	

RESULTS OF WATER WELL INVENTORY

Well No.	Owner/Location	Depth of Well (ft.)	Depth to Water Table (ft.)	Depth to Water Stratum (ft.)	Well Lift	Well Type	Age of Well	Sewage Disposal Distance & Direction from Well	Barnyard Distance & Direction from Well	Nitrate Conc. (mg/ℓ)	Remarks
463	A. G. Glass SE Miles	90 R			Wind	Cased	Old	30' N	3'	120	
464	Victor Schwertner 9M SW Ballinger	30 R		30	Electric	Cased		200Y S		326	
469	Harvey Gulley ½M E Rowena	110 R		45	Electric	Cased		200Y E		288	
471	Tocho Alverdo in Rowena	40 R			Wind	Cased	Old	30' S of house		80	
473	Arnold Fuchs 9M SW Ballinger	55 R		48	Electric	Plastic	New	200' W	15' S	336	Producing well
	Arnold Fuchs 9M SW Ballinger	35 M	10.3 M		Wind broken	Cased	Old	200' W			Deserted windmill
	Arnold Fuchs 9M SW Ballinger	31 R		27		Caved in					Caved in well
474	Clarence Hallmark 5.5M NE Ballinger	20 M	4.5 M		Electric Pump	Dug	New	¼M SW		·0.4	45 cattle/year grazed
480	Ralph Russell 2M SW Valley View	24 R	14 R	14	Electric pump	Dug	Old	600' N 20° W		220	
484	Joe T. Haechten 9½M S Ballinger	90 R		47	Wind	Cased		¼M W	¼M W	336	
493	Mrs. C. H. Midgley South Ballinger	30 M	30 M		Wind	Dug	Old	100' NW	200' N	200	
494	W. J. Kahlig 9M S Ballinger	33.6 M	4 M			Cased		50' E		809	

RESULTS OF WATER WELL INVENTORY

Well No.	Owner/Location	Depth of Well (ft.)	Depth to Water Table (ft.)	Depth to Water Stratum (ft.)	Well Lift	Well Type	Age of Well	Sewage Disposal Distance & Direction from Well	Barnyard Distance & Direction from Well	Nitrate Conc. (mg/ℓ)	Remarks
495	W. J. Kahlig 9M S Ballinger	65 R			Wind	Cased	Very old	100Y E		1365	
496	Arnold Holubec 4M SE Rowena	60 M	31.6 M	50	Electric	Cased	New	100' E		130	
503	Travis Barrett 1M S Norton	67 R	40 R		Electric Pump	Cased	Old	36' S		149	
506	Ben Wilde at Bethel	72 R		72	Electric	Cased	New	200Y W	200Y W	221	
508	Gene Virden 5.5M NW Winters	28 M	0.5 M	18	Windmill	Cased	Old	100' S	25' W	496	
512	Ralph Lange Martin's Inn Road	41			Wind	Cased	Old 1920's	200' S		270	
513	William Urbanek 4M S Rowena	65 R		65	Electric	Cased		200Y S		130	South well
516	William Urbanek 4M S Rowena	65 R		65	Electric	Cased		180Y S		110	East well
517	William Urbanek 4M S Rowena							¼M E		94	Seep water
523	Willis Davis 5.5M NW Winters	30 M	3 M		Electric Pump	Dug	Old	100' S 65° E		304	
540	C. W. Wessels 4M SW Wilmeth	55 R	20 R		Electric Pump	Cased	Old	100' E		155	
546	Bobby Rogers 5M E Winters	60 R	20 R		Electric Pump	Cased	Old	80' N 30° W		6	20 cattle/year grazed nearby

RESULTS OF WATER WELL INVENTORY

Well No.	Owner/Location	Depth of Well (ft.)	Depth to Water Table (ft.)	Depth to Water Stratum (ft.)	Well Lift	Well Type	Age of Well	Sewage Disposal Distance & Direction from Well	Barnyard Distance & Direction from Well	Nitrate Conc. (mg/l)	Remarks
547	Ben Wilde Bethel	110 R			Wind	Cased	Old		5'	299	
551	Paul Pieper 1M N Rowena	75 M	56 M	75	Electric	Cased		100' S cesspool	100' S	294	Irrigation well at house
552	Paul Pieper 1M N Rowena	70.2 M	28 M	25 68		Plastic Casing	New				New well
553	Harvey Gulley 4M W Rowena	14.5 M	4.3 M		Wind	Cased	Old	200Y S		290	
558	Alfred Wessels 4M E Norton	60 R	24 M		Electric Pump	Cased	Old	152' N 65 E		459	
566	Duncan Hensley Wingate	90 R			Electric Pump	Cased	Old	90' N		200	
567	Duncan Hensley Wingate	90 R			Electric Pump	Cased	Old	40' N		130	
569	Henry Fowler 3M SE Hatchel	24 R	12 R		Electric Pump	Dug	Old	250' SW	200' NW	315	Well in low area
578	Charlie Matschek 3½M N Rowena	25-30 R	20 R	18-20 R	Electric	Cased				10	In gravels
591	L. R. Hancock Wingate	80 R	12 R	62	Electric Pump	Cased	Old	20' W		530	
592	Jack Pritchard 1.5M NE Wilmeth	62 R	18 R	27	Electric Pump	Cased	5 yrs.	300' S	*75' SW		*Barnyard: Horses, a few cows, chickens
597	Virgil Fuller 5M N Crews	45 M	29 M		Electric Pump	Dug	Old	*120' S			*Cesspool; 40 cattle/year graze nearby

RESULTS OF WATER WELL INVENTORY

Well No.	Owner/Location	Depth of Well (ft.)	Depth to Water Table (ft.)	Depth to Water Stratum (ft.)	Well Lift	Well Type	Age of Well	Sewage Disposal Distance & Direction from Well	Barnyard Distance & Direction from Well	Nitrate Conc. (mg/ℓ)	Remarks
599	Miles Coop Gin Miles, Texas	50 R			Electric	Cased		100' N of Gin		180	
600	Alfon Book 2M E Miles at P. Frenzels	47 R		47	Electric	Cased		200'S		190	
607	Wendell Lee 5M S. Norton	40 R	30 R		Electric Pump	Cased	Old	¼M SE		430	Past history of cattle raising
608	Fred Tidmore 2M SW Maverick	60 R	35 R		Windmill	Cased	Old	80' E		504	Deserted house
614	Walter Gerhart 10M NEWinters	44 R	0.5 M	10	Electric Pump	Dug	Old	120' S 50° W		160	Some cattle grazed nearby
616	Walter Gerhart 10M NE Winters	31 M	18.6 M		Windmill	Dug	Old			180	Well located on a long-deserted farm
626	Forrest Pohler 2N Rowena	65 R			Electric	Cased				210	
627	W. Wehlman 3M N Rowena	35 M	9.8 M		Electric	Cased		200' E		<.4	Limestone aquifer overlain by gravels
630	Roman Molter 7M SW Ballinger	49 R		39	Wind	Cased	Old 1921	½M W	½M W	270	
638	Carlton Robinson Wingate	15 R			Windmill	Dug	Old	40' N 30° W 25' W		231	
653	Earl Dorsett 5.5M NW Winters	17 M	3 M		Electric Pump	Dug	Old	60' E 70' S 60° E		365	Raised 8-10 cattle/yr. 15 years ago

RESULTS OF WATER WELL INVENTORY

Well No.	Owner/Location	Depth of Well (ft.)	Depth to Water Table (ft.)	Depth to Water Stratum (ft.)	Well Lift	Well Type	Age of Well	Sewage Disposal Distance & Direction from Well	Barnyard Distance & Direction from Well	Nitrate Conc. (mg/ℓ)	Remarks
670	P. Frenzel 2M E Miles	100 R		68	Electric	Cased		100' SE		270	
671	Paul Frenzel 2M E Miles	47.5 M	26.5 M		Wind	Cased		200' S		180	
672	George Ruppert Rowena	80 R		68	Electric	Cased	5 yr.+	40' W Cesspool		1302	
686	James Patton 2M S. Wingate	60 R			Electric Pump	Cased	Old		Located in old feedlot	120	Deserted farm
689	James Patton 2M S. Wingate	90+M	29.4 M	40 70	Electric Pump	Cased	Old.	100' S 20° E		120	
705	Ras Gideon 1.5M NE Winters	12 R			Electric Pump	Dug	Old	55' N 50° E		78	
706	Ras Cideon 1.5M NE Winters	10 M	5.3 M		Electric Pump	Dug	Old	*	**	180	*Well separated from house by a sluice; **15-20 cattle graze around well
708	Mrs. C. R. Morrison 1M N. Wilmeth	110 R			Windmill	Cased	Old	150' NE	*	299	*Appears to be near old stockpen
711	Jack King ½M W Rowena	45 R		25	Electric	Cased	New	30' + 100 SE		378	
722	Marvin Patterson 2M SW Valley View	18 R	13 R		Electric Pump	Dug	Old	200' N 80° W	Located in barnyard	351	
727	James Teplicek ½M S Rowena Farmyard	60-70 R			Electric	Cased			5' E	1620	Well located downslope from hog pens

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728	James Teplicek ½M S Rowena	54 M	6		Electric	Cased		100Y S		130	Irrigation well
729	Albert Spill 7M NE Winters	60 M	25.5 M	55	Electric Pump	Cased	New	30' S 15° E	*120' W	130	*20 cattle kept in pen
746	Carl Lewis Norton	65 R			Electric Pump	Cased	Old	110' S 35° E		100	
747	Edwin Urban 3M NW Miles	70-80 R		60	Electric	Cased	Old	100' NW		170	
773	M. R. Williams 5M NW Winters	40 R	4 R	32	Electric Pump	Dug	Old	210' S	*50' S	243	*New feedlot
775	Mrs. A. T. Williams 6M NW Winters	48 R	8 R		Electric Pump	Cased	Old	34' N 65° E		296	
784	Andrew Lange 1M E Rowena	100 R			Electric	Cased	1954	½M E	½M E	300	
786	E. F. Albro 1M NE Wilmeth	105 R	30 R	75	Electric Pump	Cased	Old	*100' NW		324	*Outhouse; has a few cows and hogs; recent tenant
805	V. D. Cooper 4.5M N Winters	36 M	5.7 M		None	Dug	New	600' NE	*	12	*Located in pasture; 100-150 cattle graze near well
806	V. D. Cooper 4.5M N Winters	22 R			Electric Pump	Dug	Old	300' E	*	<0.4	*Located in pasture; 100-150 cattle graze near well
864	W. H. Dierschke 2M NE Rowena	100 R	26.6 M		Electric	Cased		½M W of house		210	

RESULTS OF WATER WELL INVENTORY

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865	Omar Halfman 8M S Ballinger	20 M	6.6 M		Electric	Dug		25' W	50' NE	1250	Dug well by the house
866	Omar Halfman 8M S Ballinger	30 M	3.6 M		Electric	Dug				200	Olfen church well
867	Omar Halfman 8M S Ballinger	60 M	6 M		Wind	Cased	Old	50' SW	0	1898	Windmill in corral
868	Omar Halfman 8M S Ballinger	61 M	6.17 M			Cased		½M SW	½M SW	920	Location of TWDB water level recorder
869	Omar Halfman 8M S Ballinger	25 R	.5 M							243	Olfen school well
870	A. C. Wendland 4M W Miles	≈90 R			Wind	Cased			0	110	Well located next to small feedlot
1000	Smithwick in Miles	80 R		50-60	Wind	Case gravel packed		400'S	200'S	120	
1001	J. Hohensee 2M SE Miles	49 R				Dug	Old			190	Dug drainage well; interbedded limestone & marls
1002	Robert Schwertner 1M SW Rowena	20 M	4 M	18-20	Wind	Cased		200'S		280	
1003	E. R. Holubec 4M SE Rowena	70 R		63			New	150' S		820	
1004	Werner Lange Rowena	115 R		76	Electric	Cased				360	
1005	Lyle & Lyle 2M S Ballinger	42 M	16.7 M			Dug	Old				

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1006	H. H. Gulley 2½M S Ballinger	60 M	22 M		None	Cased	Old	50' S	3' S	1470	Location of TWDB water level recorder. A few cattle died at this well
1007	H. H. Gulley 2½ M S Ballinger	30 M	1.7 M	15	Electric	Cased	4 yrs.	¼M E	¼M E		
1008	J. Hohensee 2M E Miles	100 R	60 R		Electric	Cased	Old	300' N		59	
1009	Arthur Halfman 1½M NW Lowake	45 R	25-30 R	45	Electric	Cased		50' E		112	
1010	Cmereck 1½M N Miles	67-70 R		67-70	Electric	Cased	10 yrs.	50'		110	
1031	Ludwig Schwertner 1½M NE Rowena	70 M	25 M		Wind	Cased					
1032	Joe Pfluger 3M SW Ballinger	40 R			Electric	Cased	New	250' N		25	
1033	Gus Frey 2M S Ballinger	60 R			Electric	Cased		100' N			No sample; broken pump; few cattle died from water
1034	Frieda Backhous 5M S Rowena	60 R			Wind	Cased		50' SW	5' N	2162	Highest NO_3 in county; no obvious source of NO_3
1111	Jack Bishop 5M NW Winters	60 R	10 R	26	Electric Pump	Cased	Old	100' S 55° W 70' N 80° W		198	Grazes some cattle

RESULTS OF WATER WELL INVENTORY

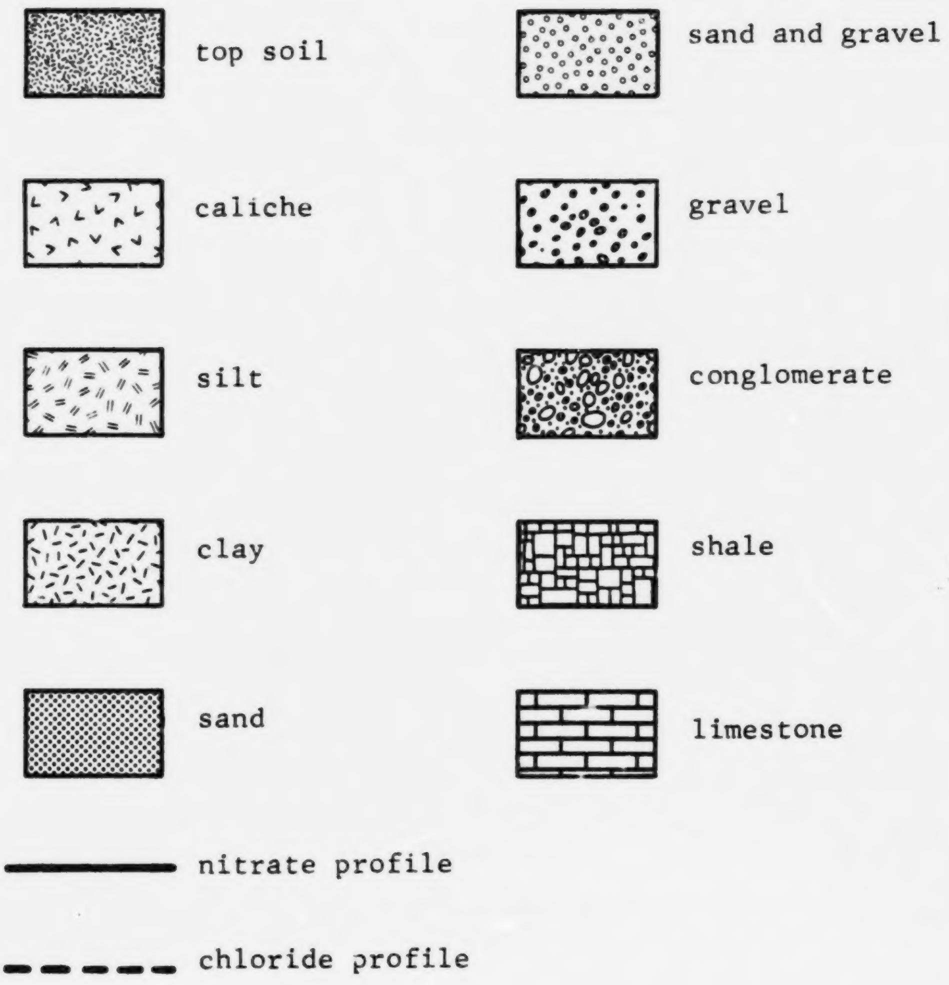
Well No.	Owner/Location	Depth of Well (ft.)	Depth to Water Table (ft.)	Depth to Water Stratum (ft.)	Well Lift	Well Type	Age of Well	Sewage Disposal Distance & Direction from Well	Barnyard Distance & Direction from Well	Nitrate Conc. (mg/ℓ)	Remarks
1112	Dewitt Bryan 2M NW Wilmeth	80 R			Electric Pump	Cased	Old	300' NE	50' W	165	10-15 cattle, chickens, hogs
1113	Valley Creek 0.5M S Wingate									28	
1114	Valley Creek 2M E Norton									26	
1115	Bobby Rogers 5M E Winters	50 R		32	Electric Pump	Cased	1 yr.			130	New house located on a hill over 100 yds. east of old house
1116	Frank Carter 6.5M SE Winters	70 R		25 50	Electric Pump	Cased	1 yr.	125' N 40° W	110' NE	100	See Well No. 445
1117	James Brown 5M SE Winters	32 M	9 M		Electric Pump	Dug	Old	100' E	30' N	210	12-15 cattle
1118	R. T. O'Dell 4.5M N Winters	14 M	4.4 M		None	Dug	1 yr.			110	Located far out in pasture; 125-150 cattle grazed
1119	R. T. O'Dell 4.5M N Winters	14 M	4.7 M		None	Dug	1 yr.			23	Located far out in pasture; 125-150 cattle grazed
1120	Dude Dunn Wingate				Electric Pump	Cased	Old	100' NE		76	
1121	Walter Niehaus Norton				Electric Pump	Cased	Old	80' N 10° W		51	
1125	John Grohman 3.5M SW Winters	Stock Tank						300' E of house		15	See Well No. 255

RESULTS OF WATER WELL INVENTORY

APPENDIX III

PROFILES FOR SOIL NITRATE AND SOIL CHLORIDE

INDEX TO LITHOLOGY


top soil
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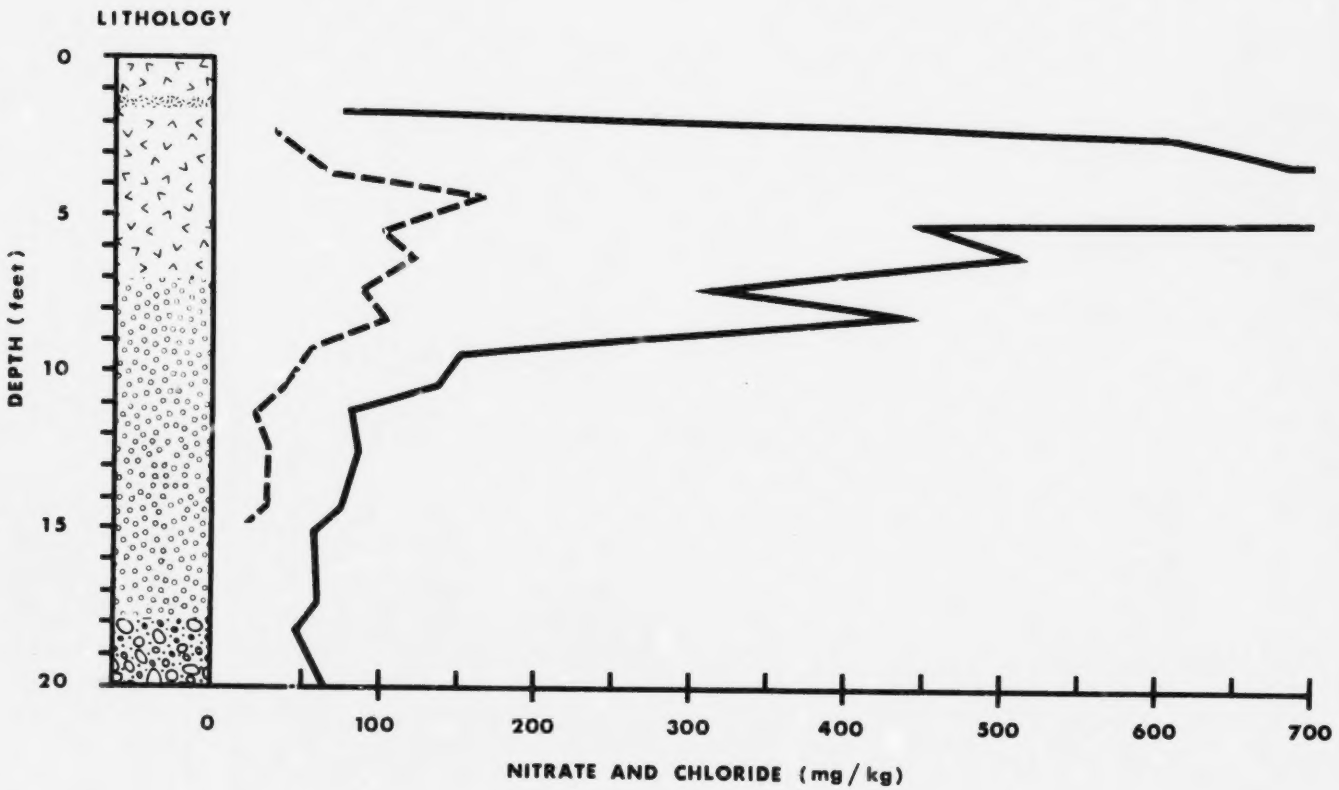
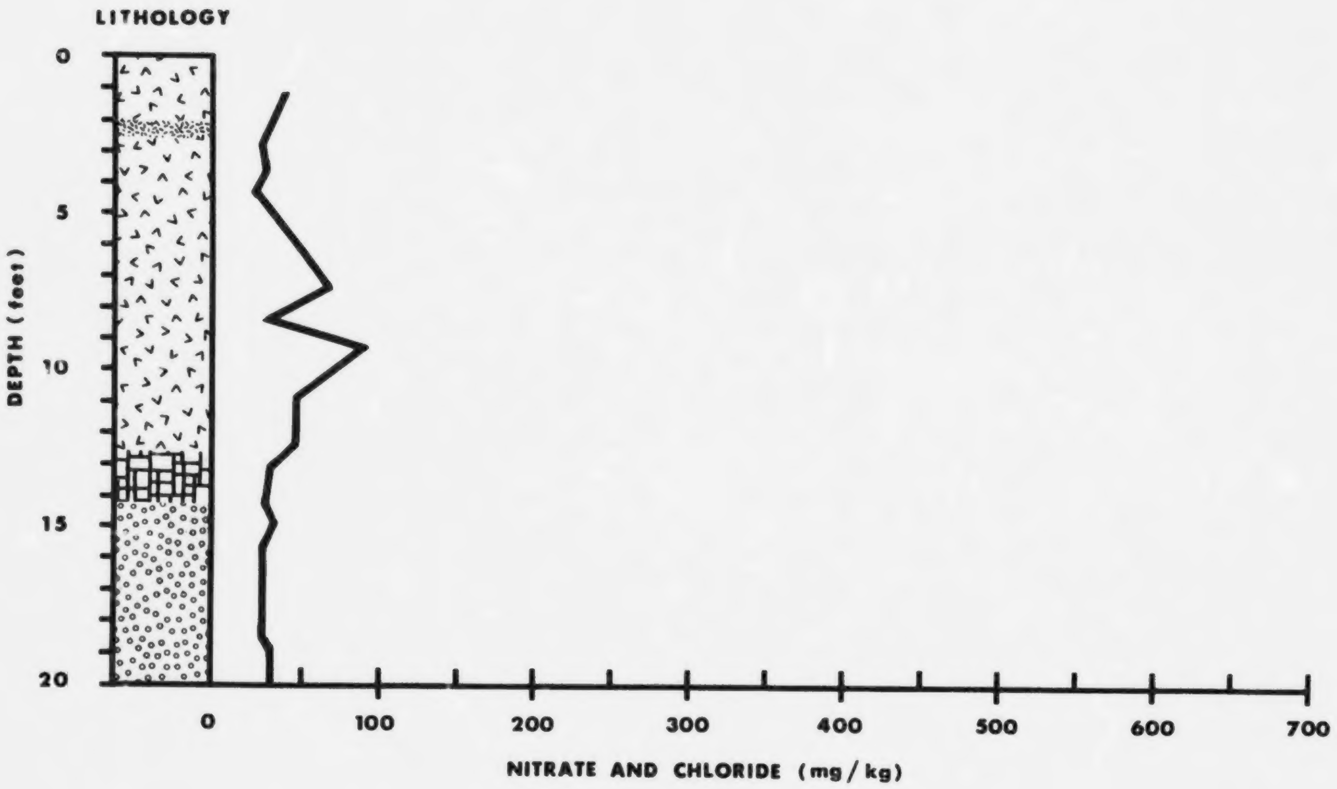
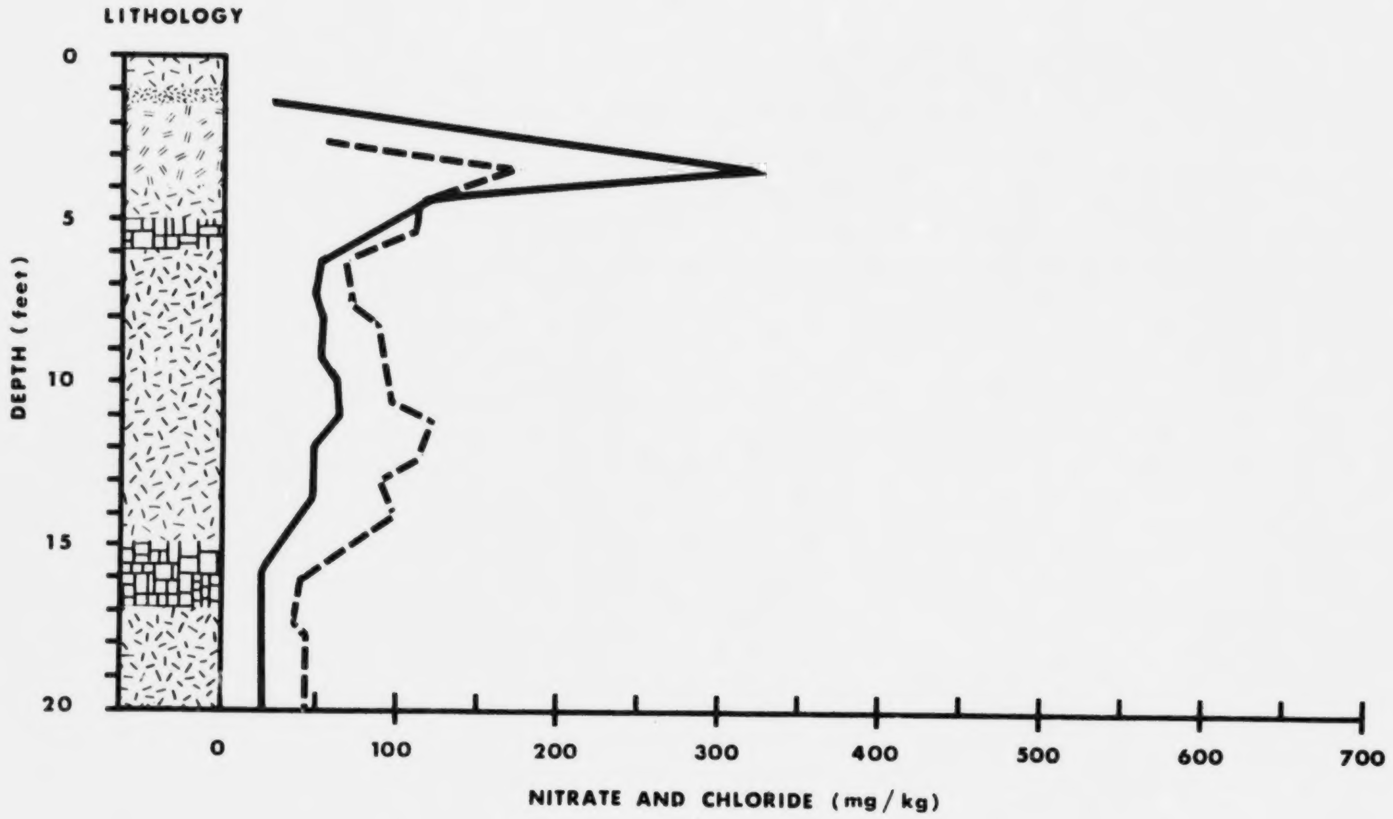
gravel
silt
conglomerate
clay
shale
sand
limestone
nitrate profile
chloride profile



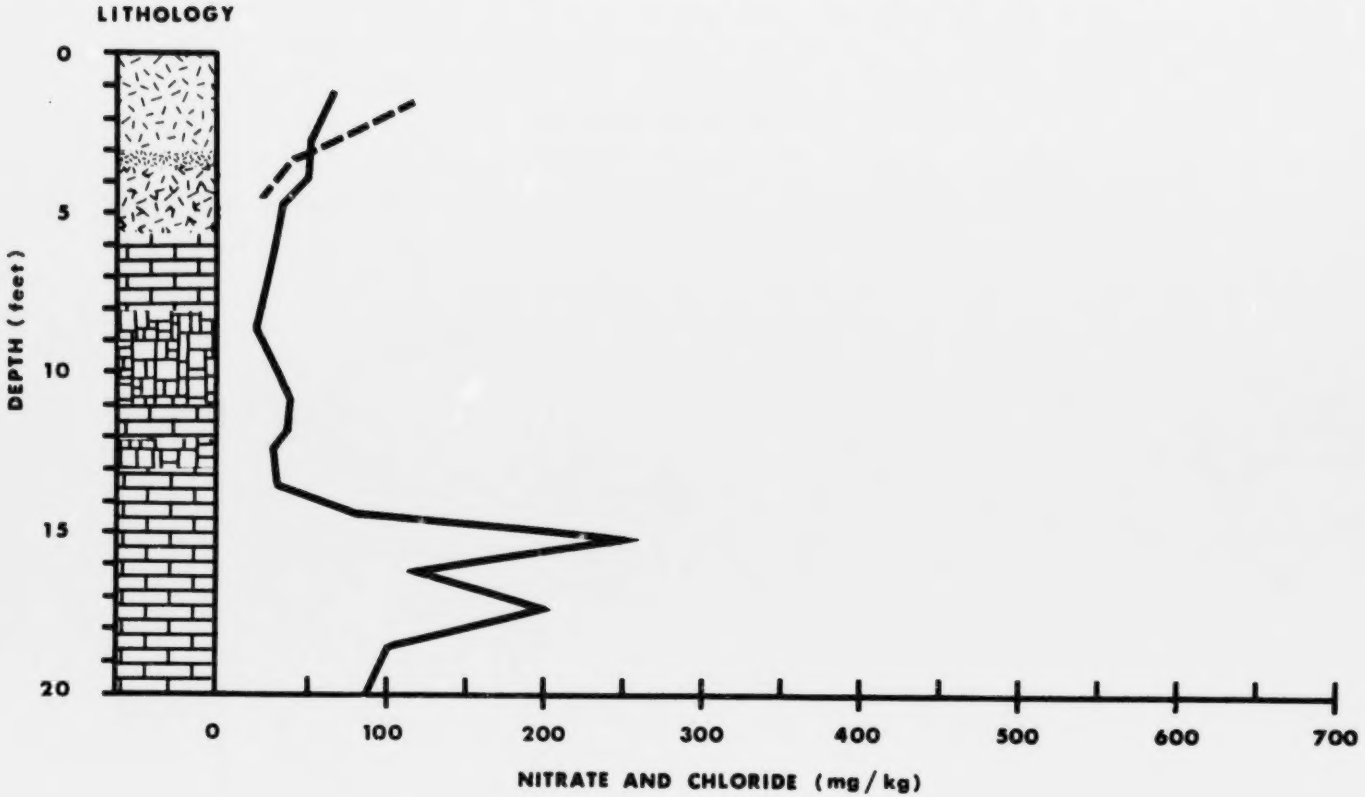
Hole 1. Located 10 feet south of well 369 (326 ppm Nitrate, 22 feet to water) which was used as a watering hole for cattle for fifty years. Chlorides are quite low in comparison to the nitrate present. 2,080 #/acre-foot.



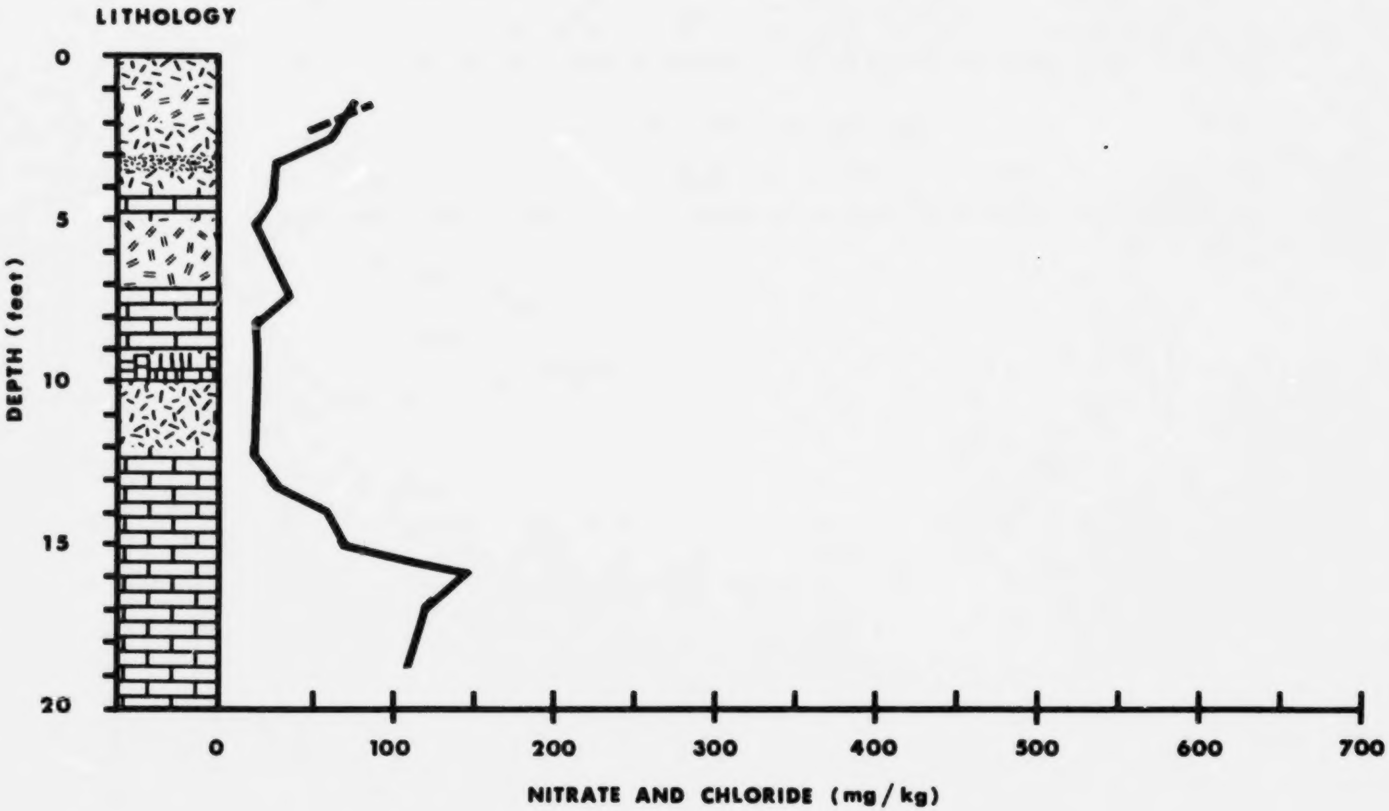
Hole 2. Located 100 yards south of well 369 (326 ppm Nitrate, 22 feet to water) which was used as a watering hole for cattle for fifty years. Chlorides are quite low in comparison to the nitrate present. 2,080 #/acre-foot.



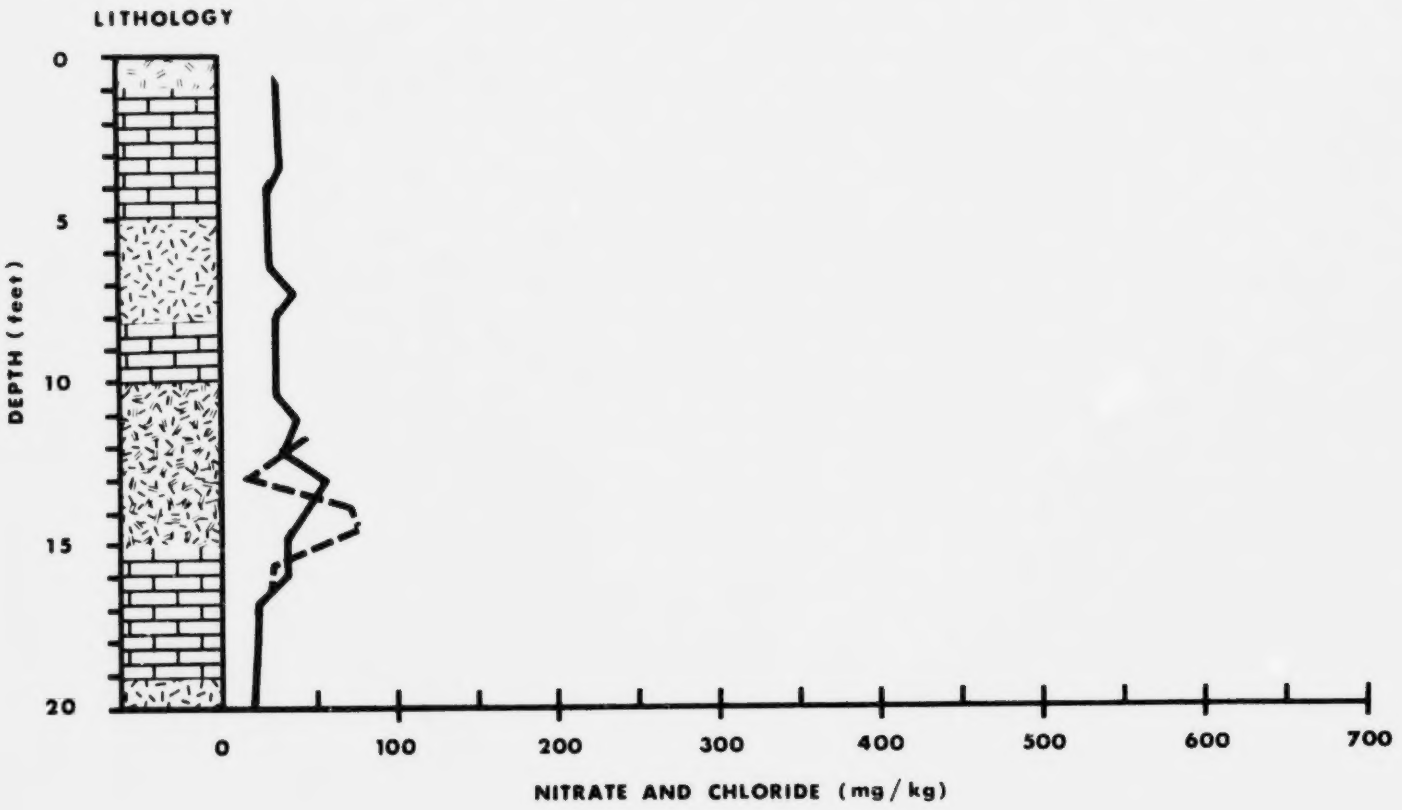
Hole 3. Located 250 yards west of well 369 (326 ppm nitrate, 22 feet to water). The high nitrate and good correlation with chloride indicate animal wastes, although there is no history or reason for any particular concentration of cattle at this site. 513 #/acre-foot.



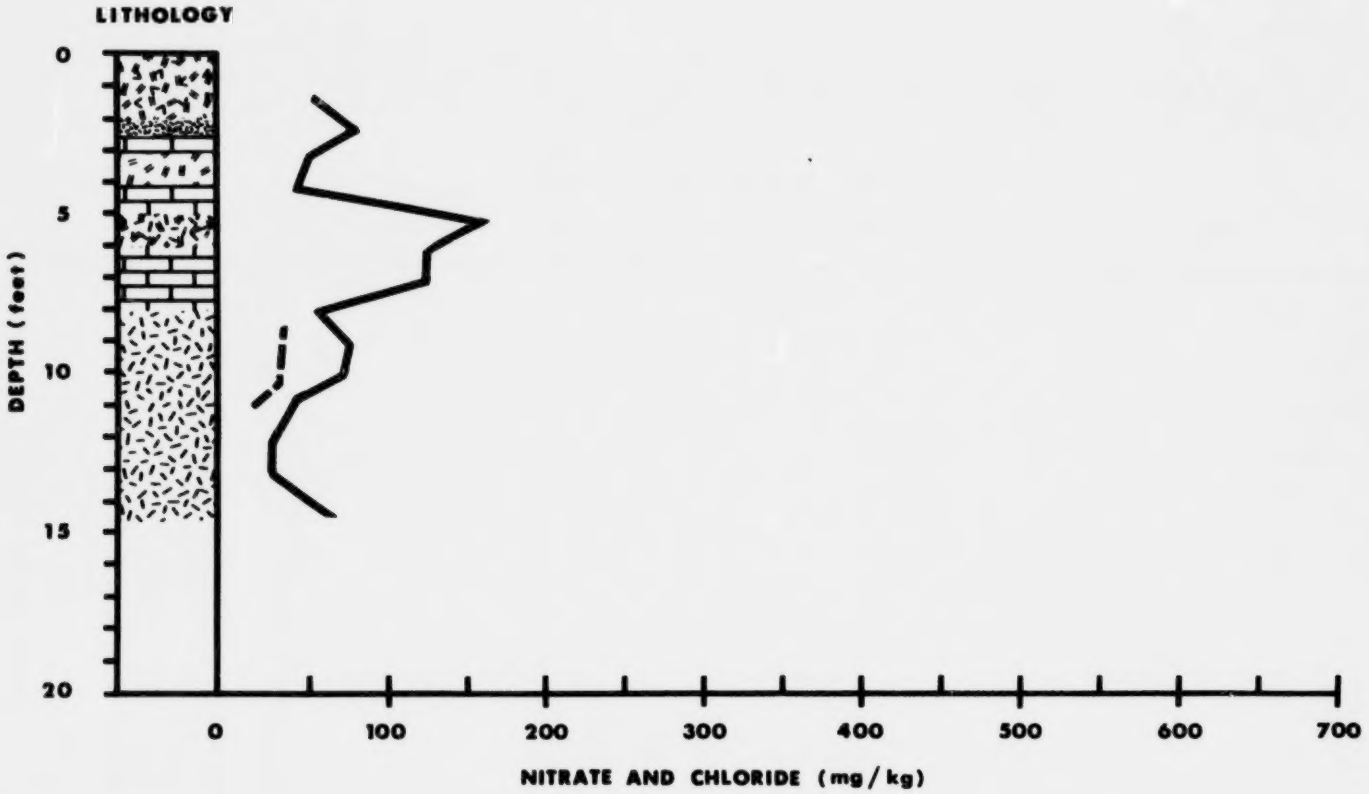
Hole 4. Located in a mesquite pasture ¼ mile west of well 419 (240 ppm nitrate) (see map following Hole 5). The high nitrate concentration below 14 feet is possible due to deposition from groundwater flowing laterally in a permeable limestone. The chloride is very low. 327 #/acre-foot.



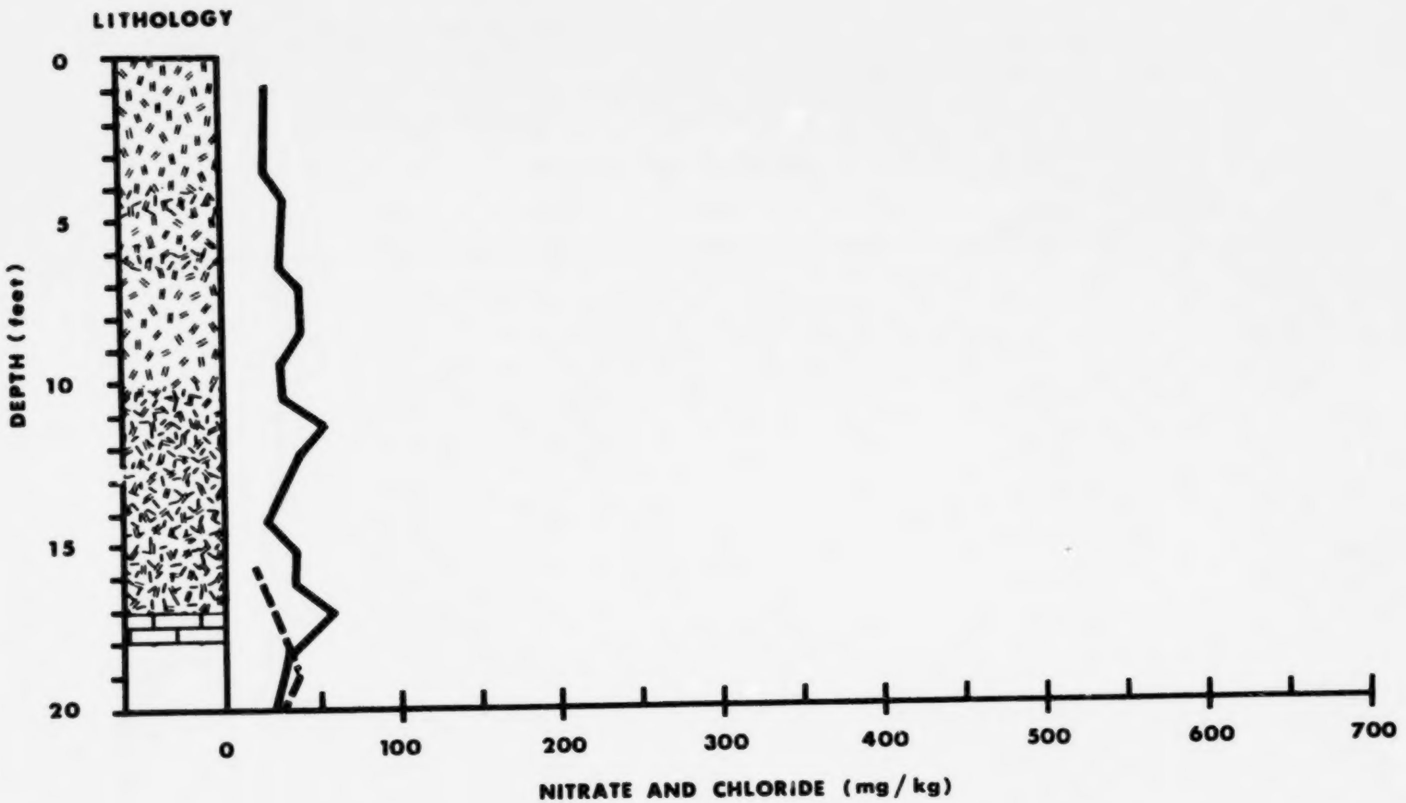
Hole 5. Located 100 feet north of Hole 4 in a pasture with no mesquite. High nitrate and low chloride in the limestone below 14 feet.



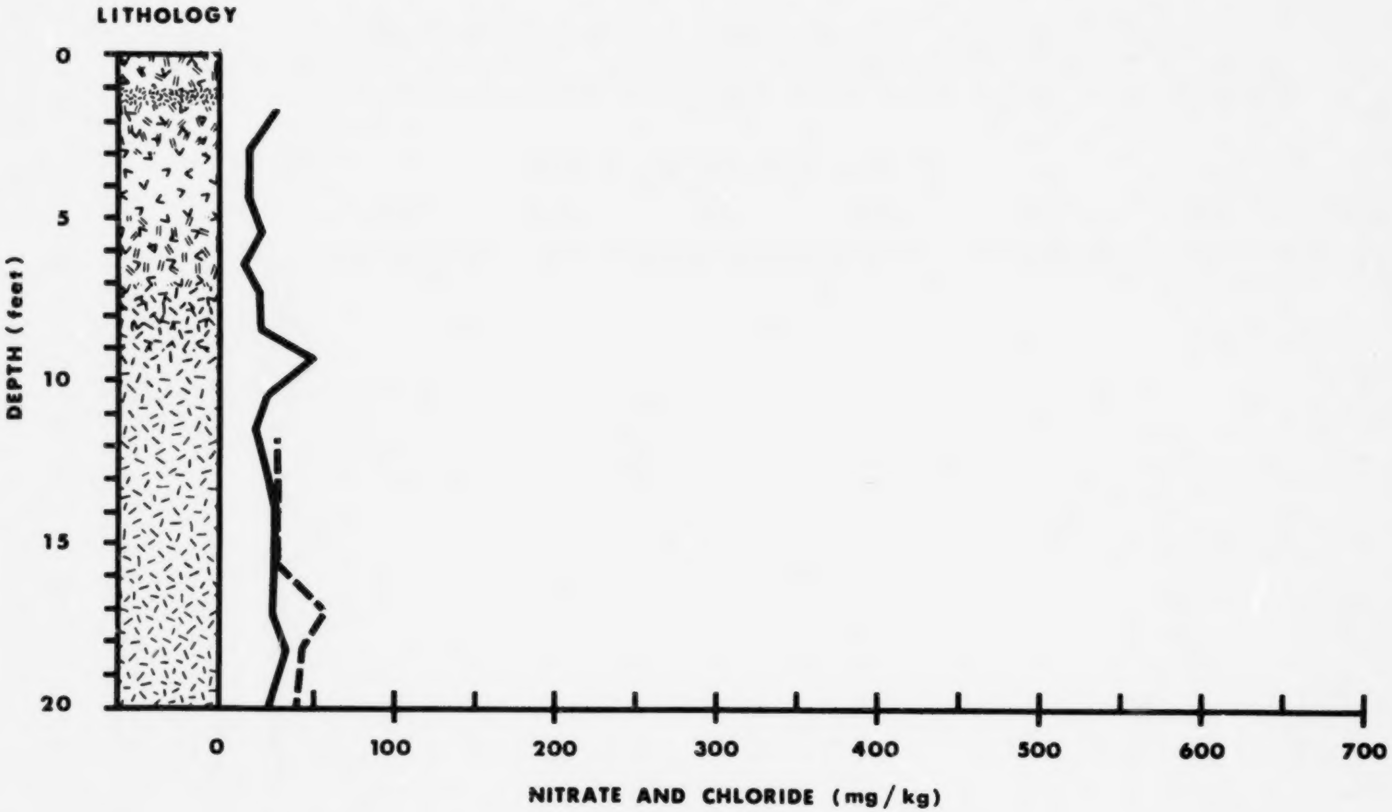
Hole 6. Located 50 feet northwest of well 116 (312 ppm nitrate, 14 feet to water), which was used as a watering hole for cattle. Low nitrate and low chloride. 180 #/acre-foot.



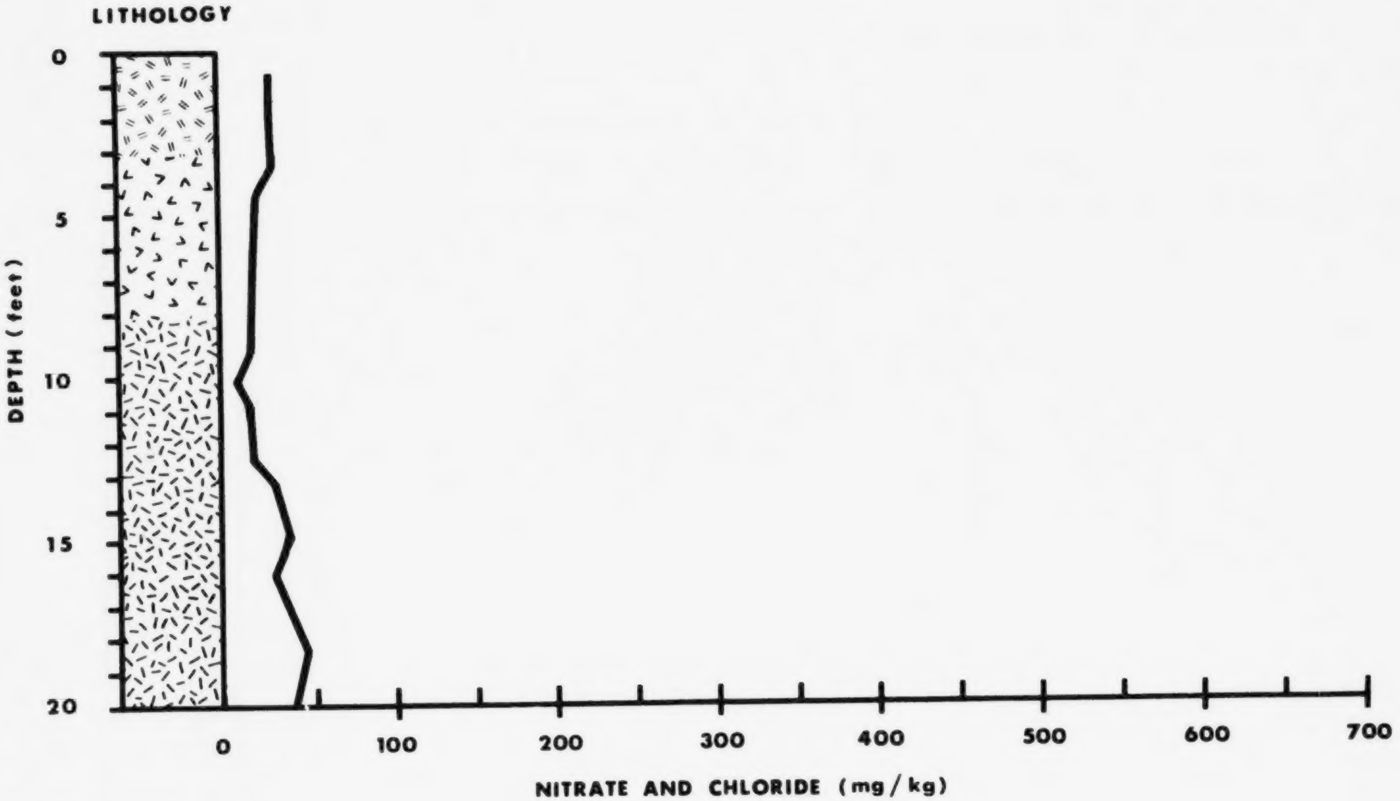
Hole 7. Located 20 feet east of well 113 (419 ppm nitrate, 2 feet to water). No history of livestock, fertilizer, or human habitation at this site. The nitrate is quite high while chloride is very low. 427 #/acre-foot.



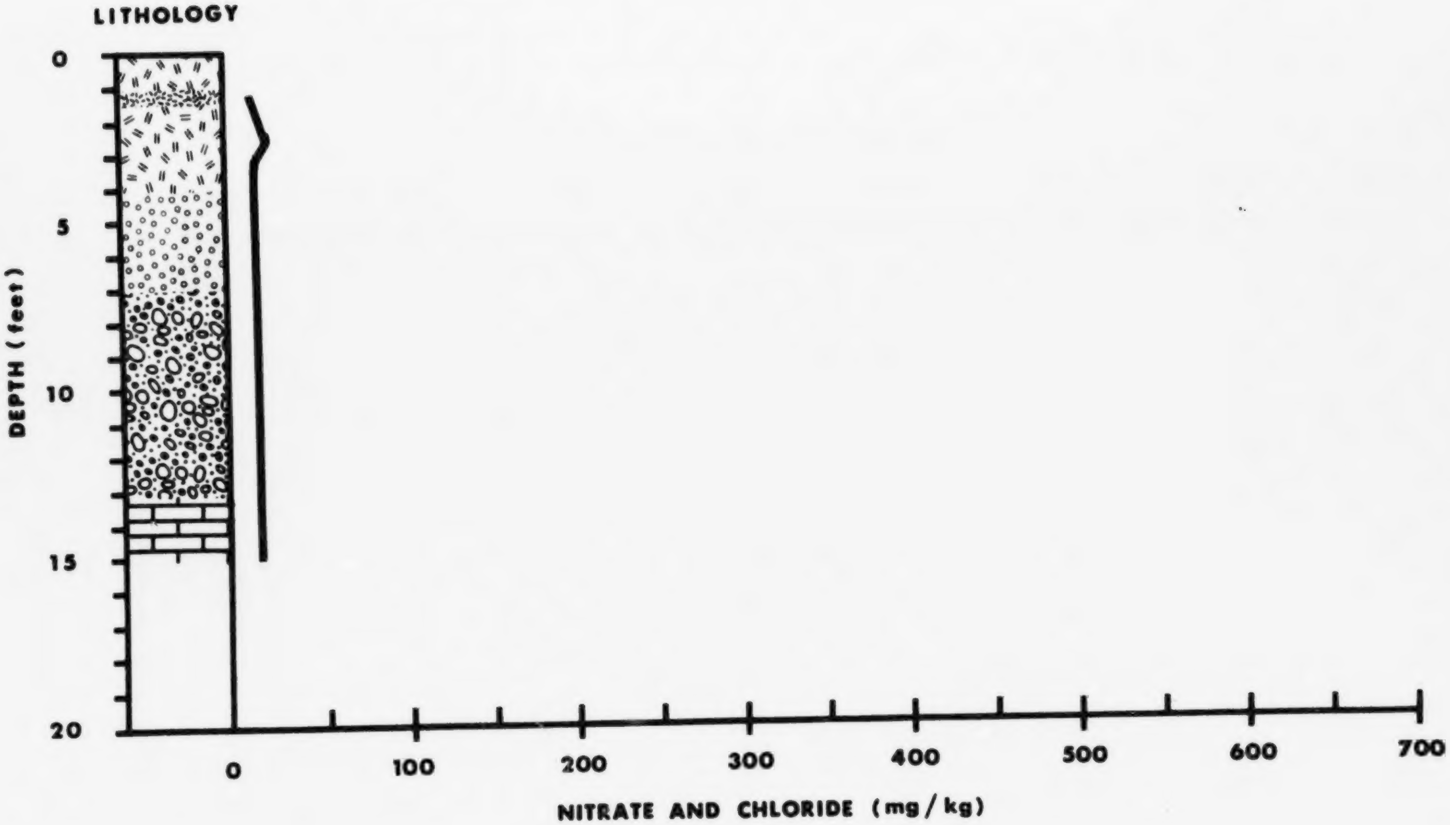
Hole 8. Located in a cotton field 250 yards south of well 113 (419 ppm nitrate, 2 feet to water). No history of livestock, fertilizer, or human habitation near this hole. Low chloride. 287 #/acre-foot.



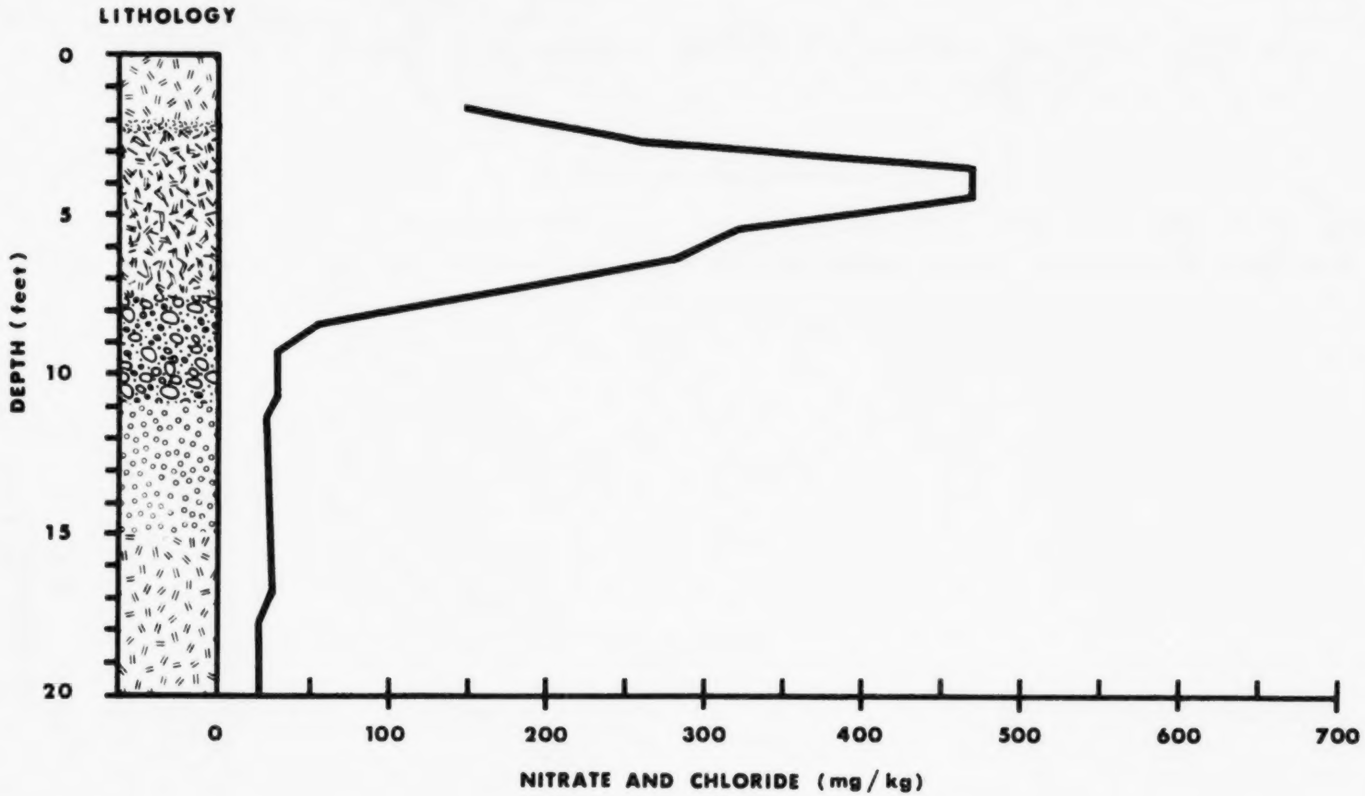
Hole 9. Located ½ mile west of well 6 (886 ppm nitrate) on top of a hill in a pasture where cattle are raised. Nitrate is fairly low, chloride very low above 12 feet. 167 #/acre-foot.



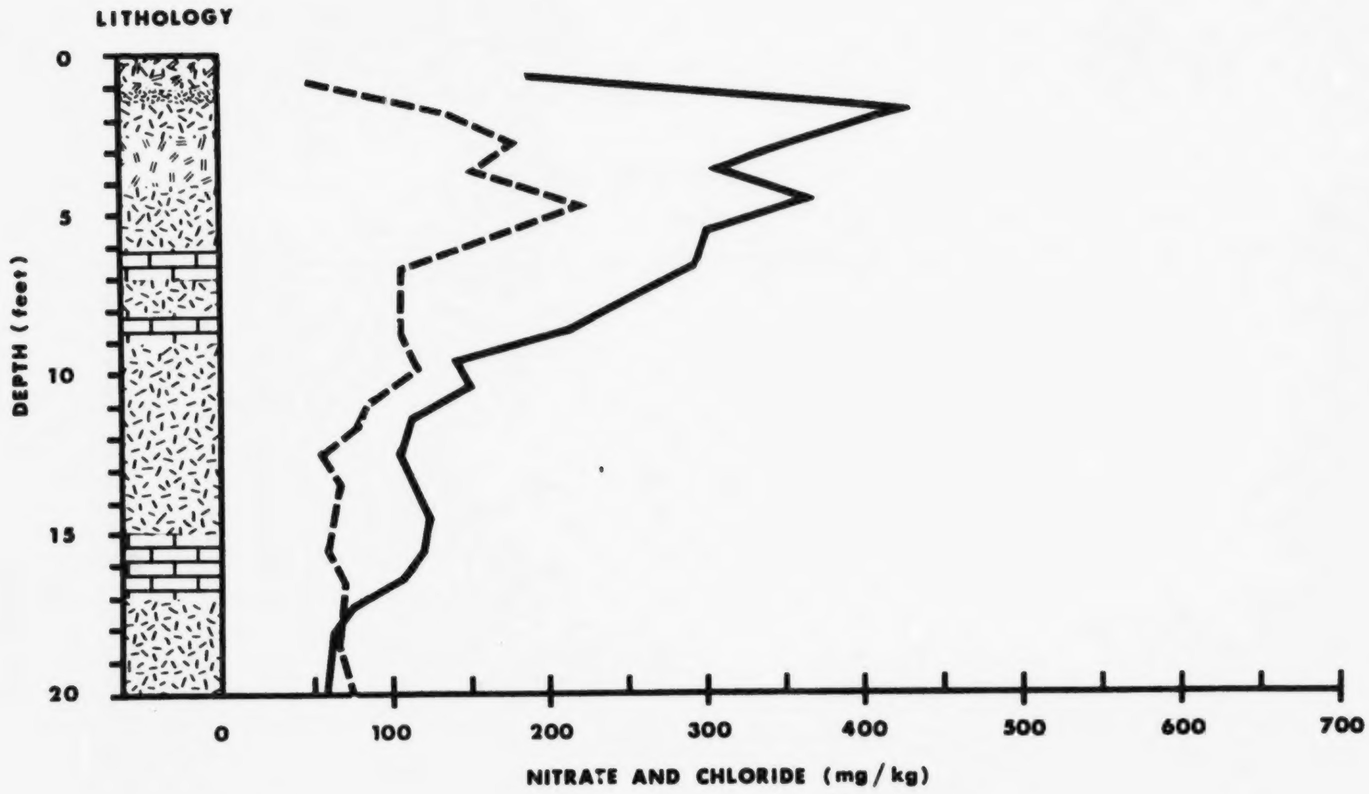
Hole 10. Located ¼ mile west of well 6 (886 ppm nitrate) on the side of a hill in a pasture where cattle are raised. Chloride is very low, nitrate is fairly low. 173 #/acre-foot.



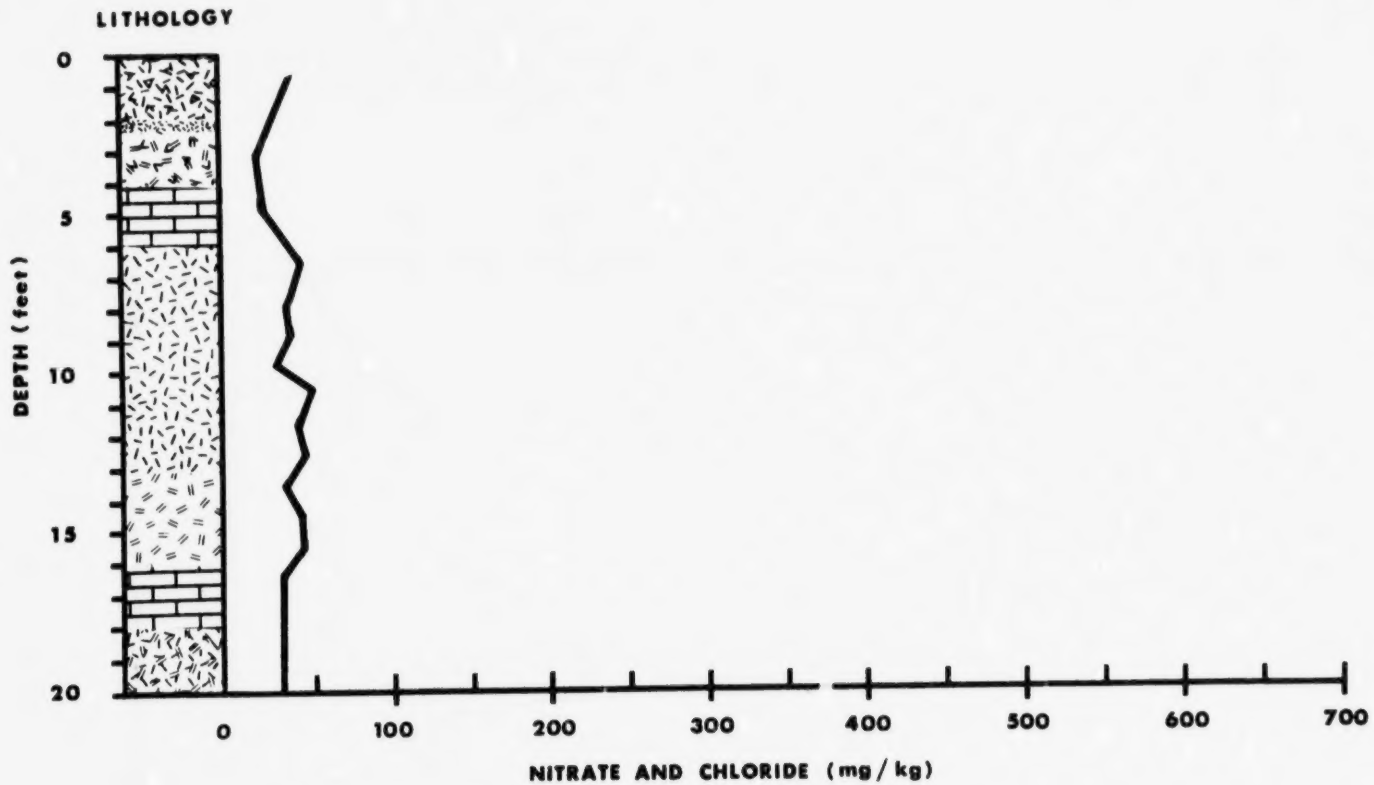
Hole 11. Located ¼ mile north of well 60 (5 ppm nitrate) in Colorado River Terrace. Nitrate is low, chloride is very low. 113 #/acre-foot.



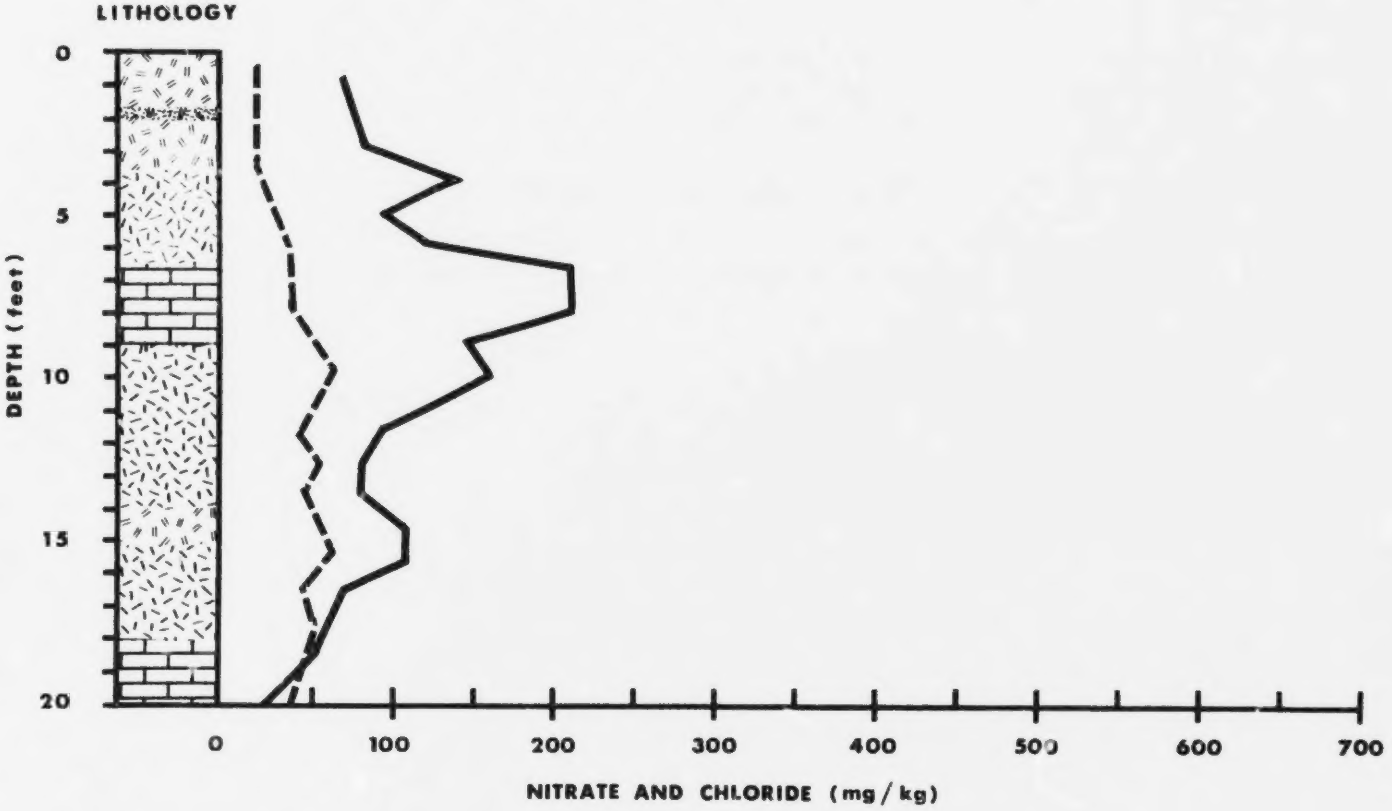
Hole 12. Located on a turn row in a cotton field ¼ mile south of well 234 (387 ppm nitrate, 12 feet to water). There is no history of livestock, fertilizer, or human habitation at this site. Chloride is very low and nitrate is very high. 947 #/acre-foot.



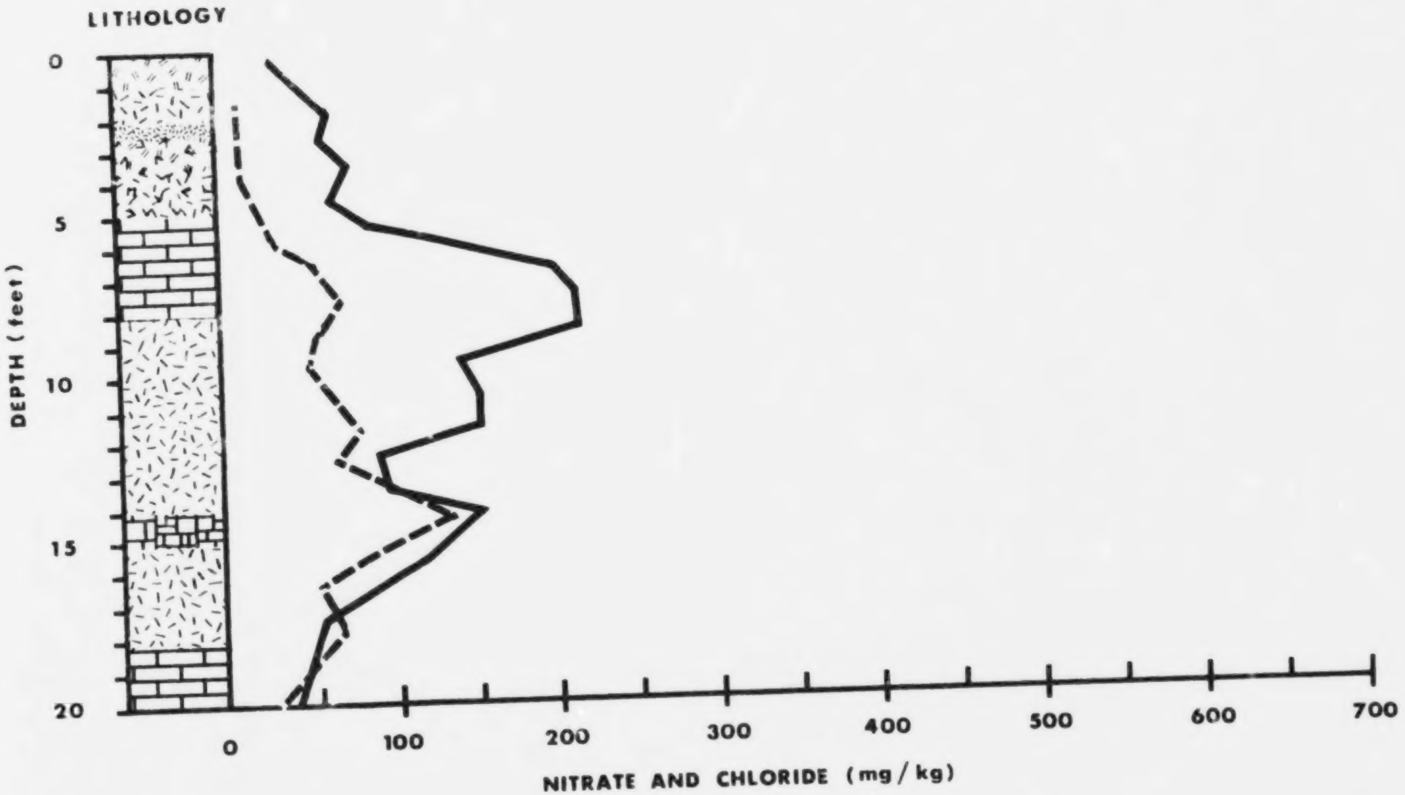
Hole 13. Located 10 feet south of well 1006 (1470 ppm nitrate, 22 feet to water) at a deserted corral. A herd of cattle died from nitrate poisoning at this well (1968). Nitrate and chloride are high. 1380 #/ acre-foot.



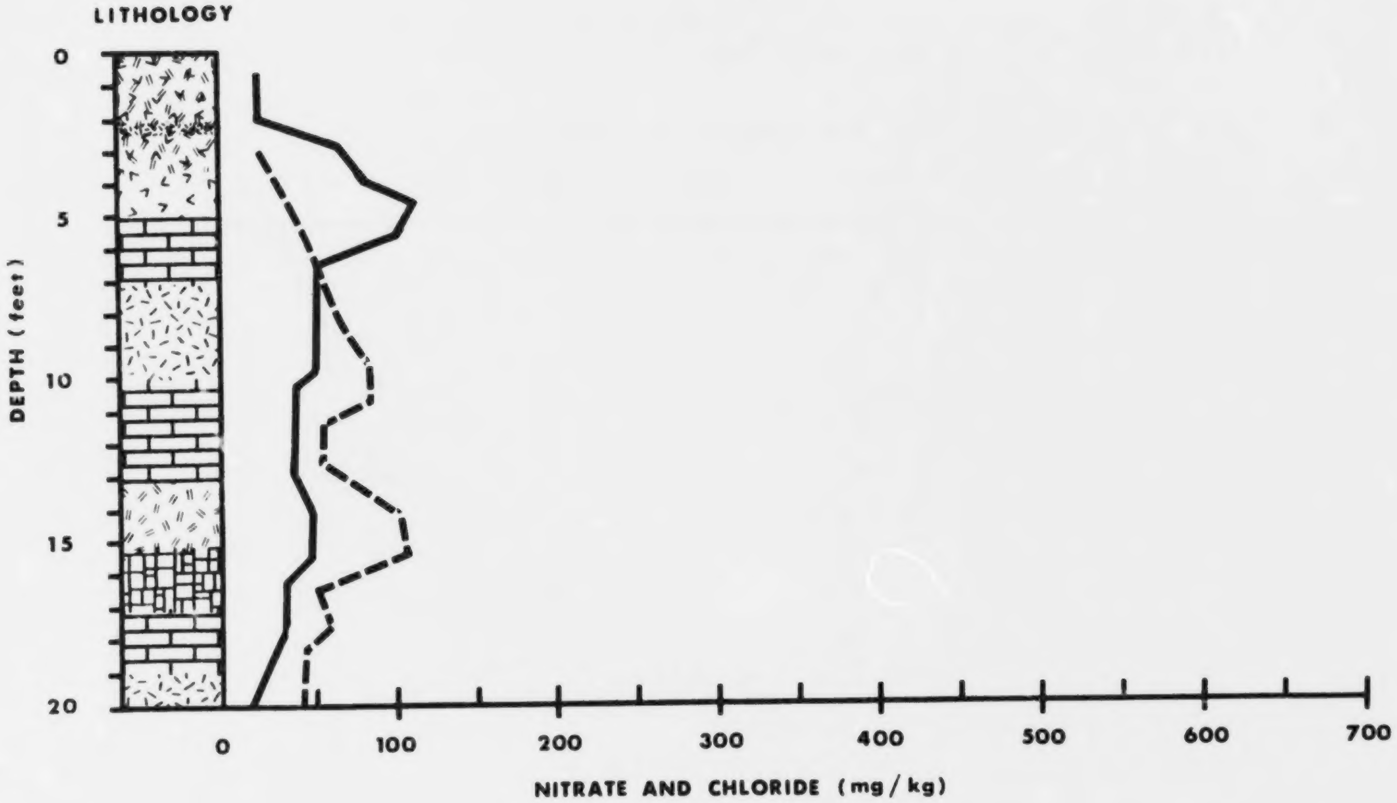
Hole 14. Located in a maize field 100 yards south of well 1006 (1470 ppm nitrate, 22 feet to water). No history of livestock, fertilizer, or human habitation at this site. Chloride is very low, nitrate is fairly low. 240 #/acre-foot.



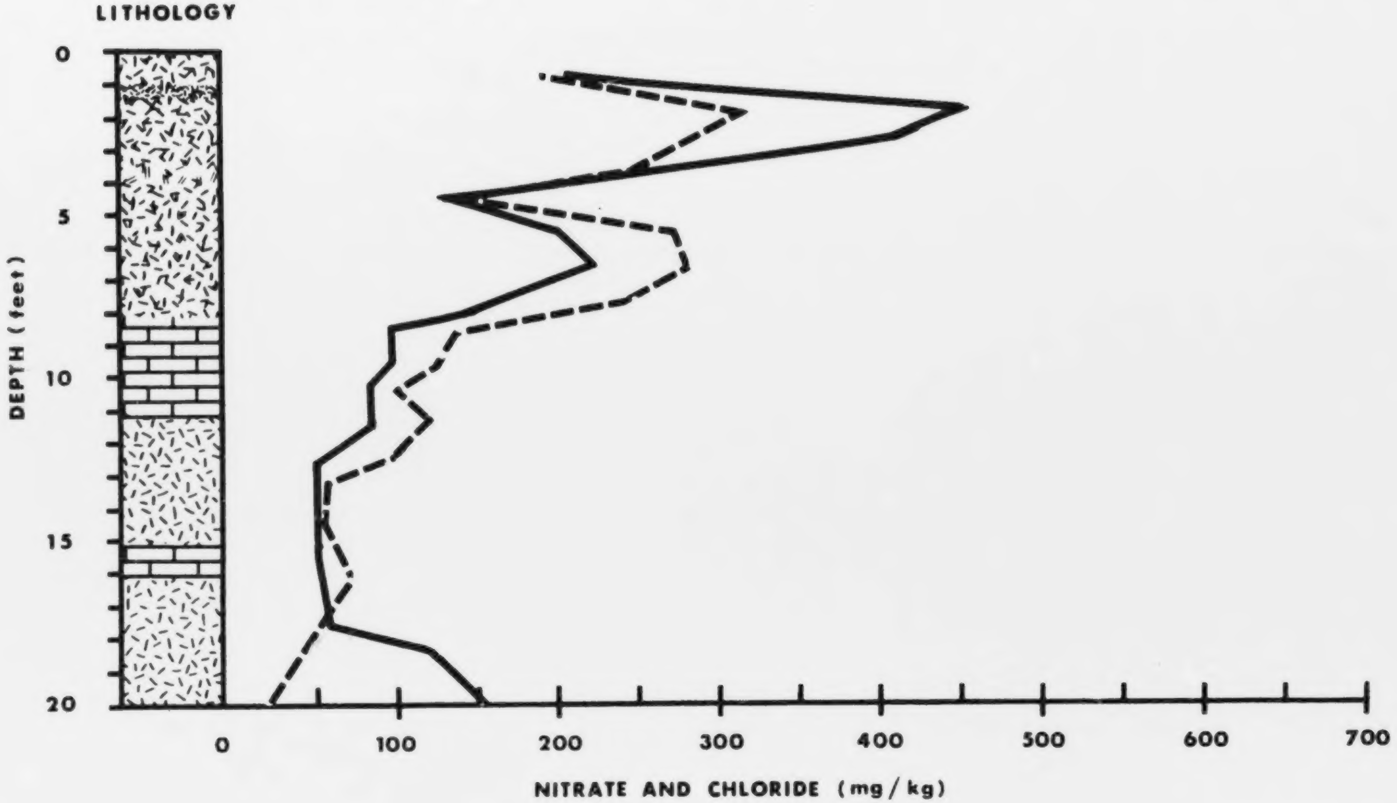
Hole 15. Located at site of old barnyard, 250 yards south of well 1006 (1470 ppm nitrate, 22 feet to water). Chloride is fairly low, nitrate is fairly high. 760 #/acre-foot.



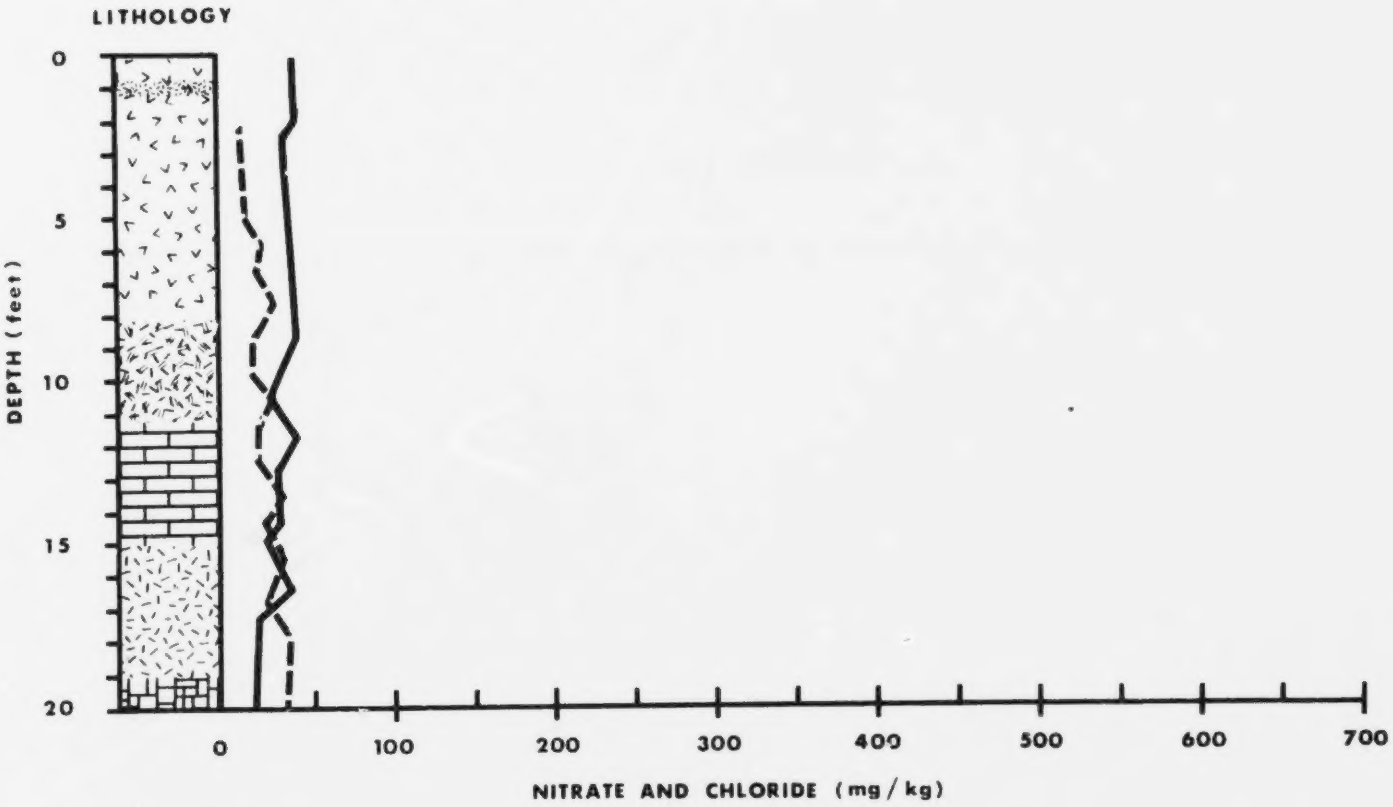
Hole 16. Located at site of torn down house of old farm, 250 yards south of well 1006 (1470 ppm nitrate, 22 feet to water). Fairly good nitrate-chloride correlation. 733 #/acre-foot.



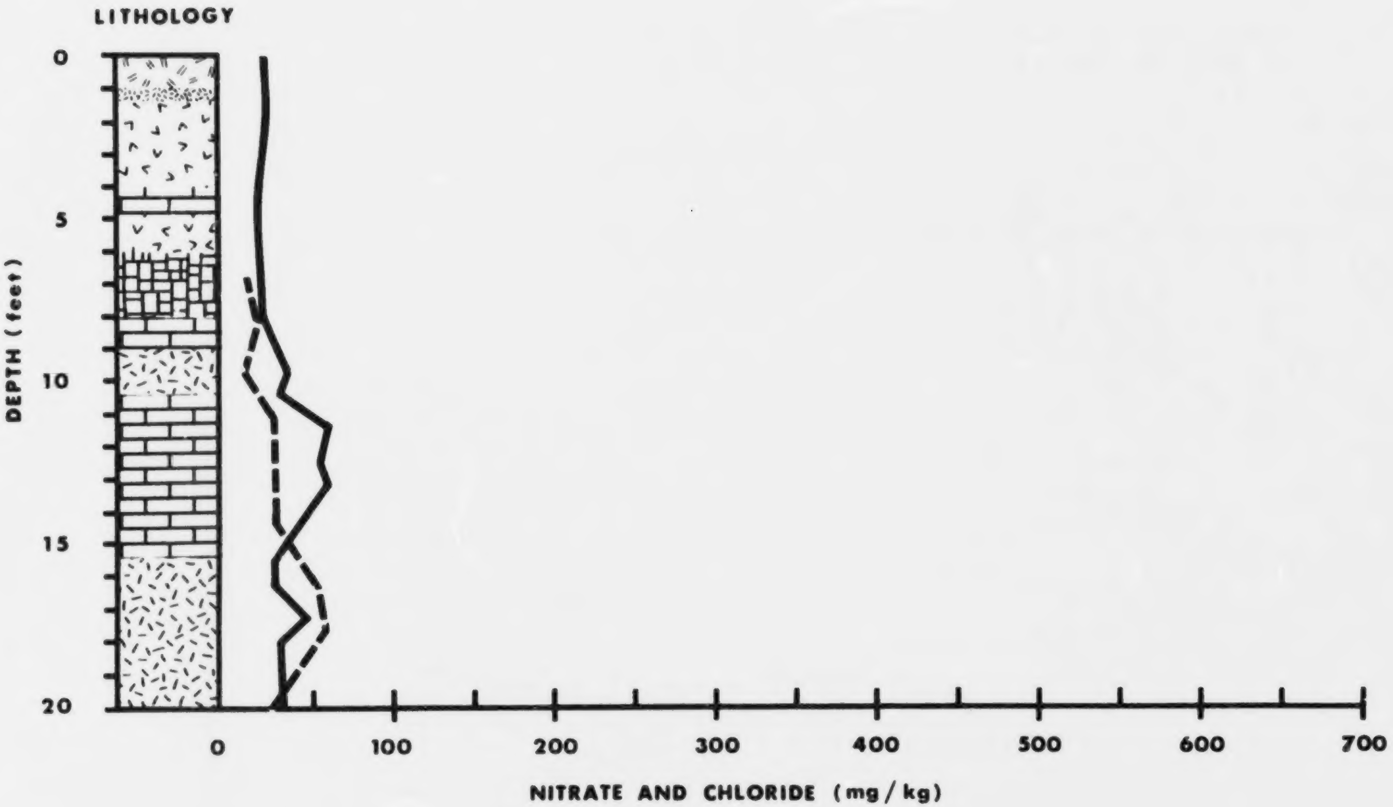
Hole 17. Located 30 feet southeast of well 386 (315 ppm nitrate, 21 feet to water) and next to a caliche pit. There is a history of a few cattle at this site. Fairly good nitrate-chloride correlation. 360 #/acre-foot.



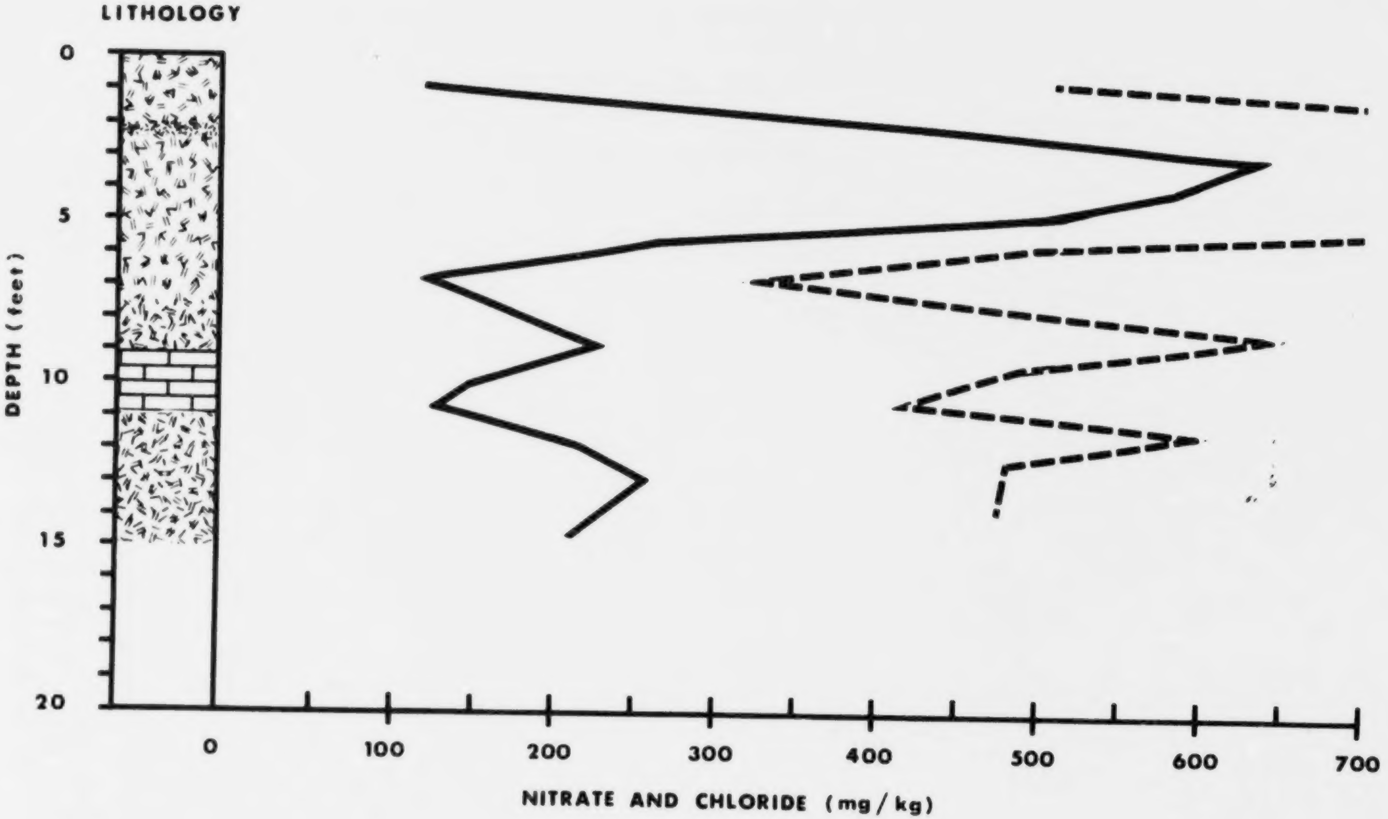
Hole 18. Located 5 feet north of well 388 (1428 ppm nitrate, 7 feet to water) and 5 feet south of a hog pen. Nitrate and chloride are very high and correlate extremely well. 1,093 #/acre-foot.



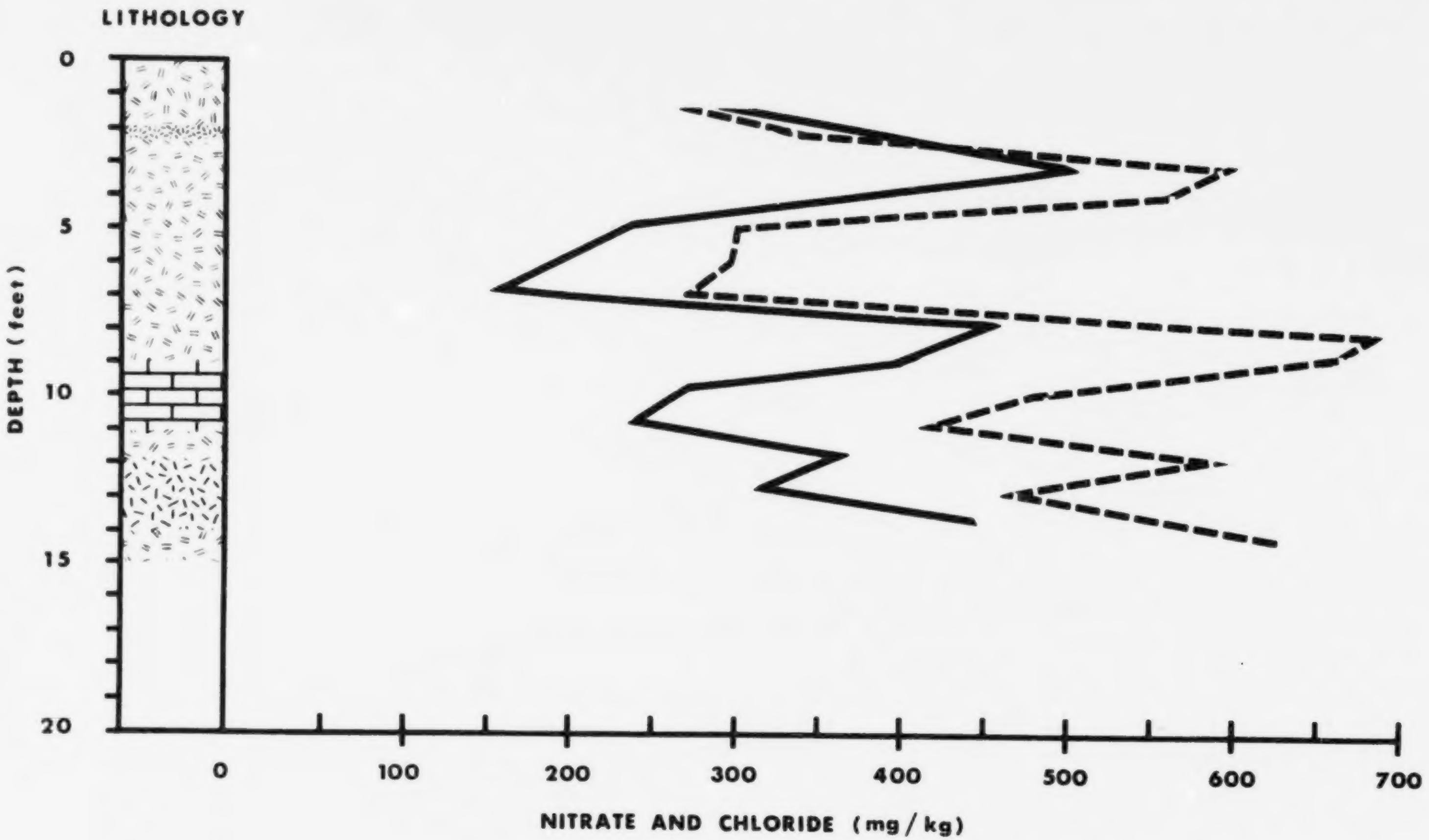
Hole 19. Located 250 feet west of well 388 (1428 ppm nitrate, 7 feet to water). Nitrate and chloride are low, but correlate well. 247 #/acre-foot.



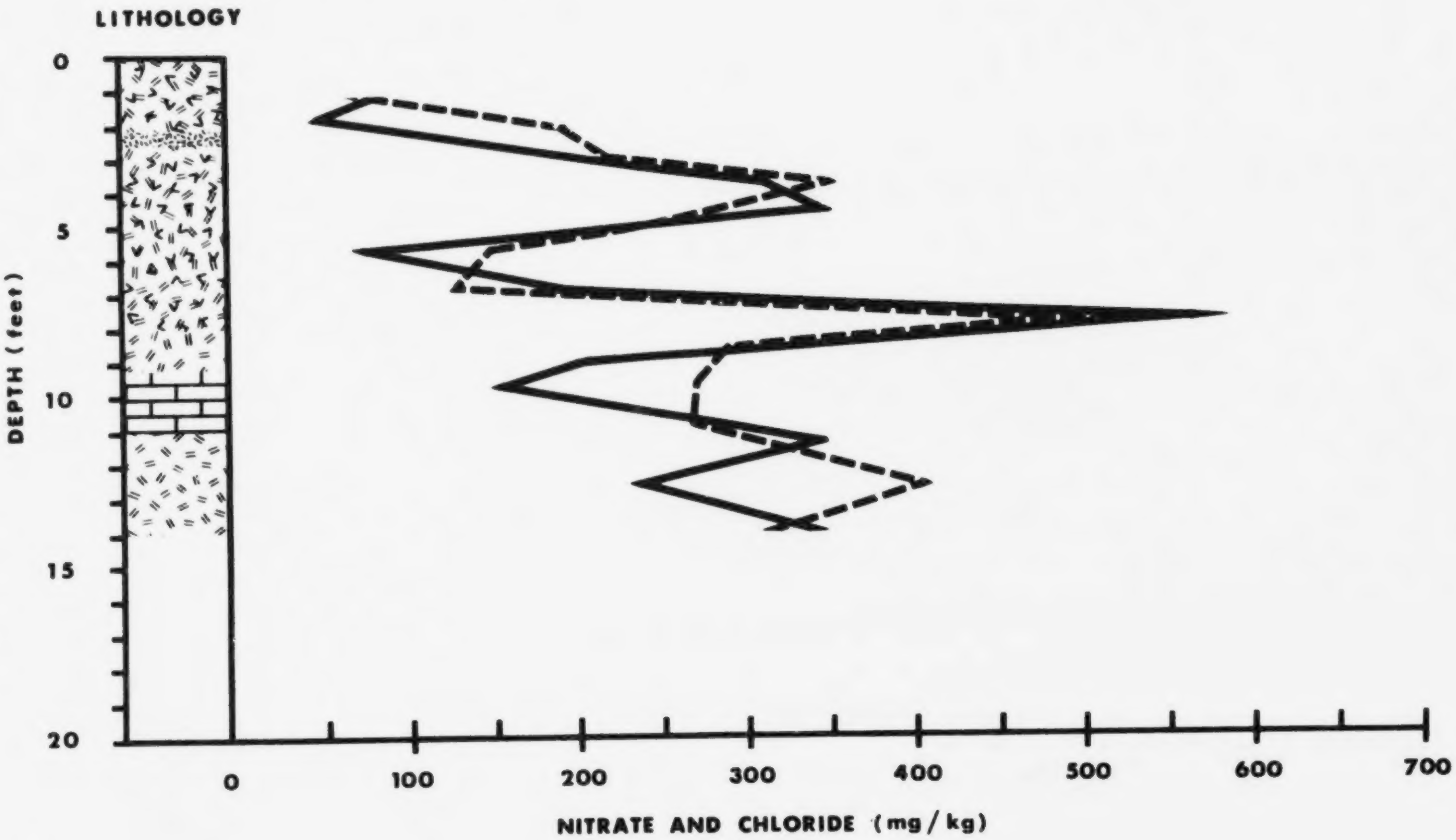
Hole 20. Located 75 feet east of well 867 (1898 ppm nitrate, 6 feet to water) and 30 feet south of two septic tank laterals. Nitrate and chloride are fairly low. 240 #/acre-foot.



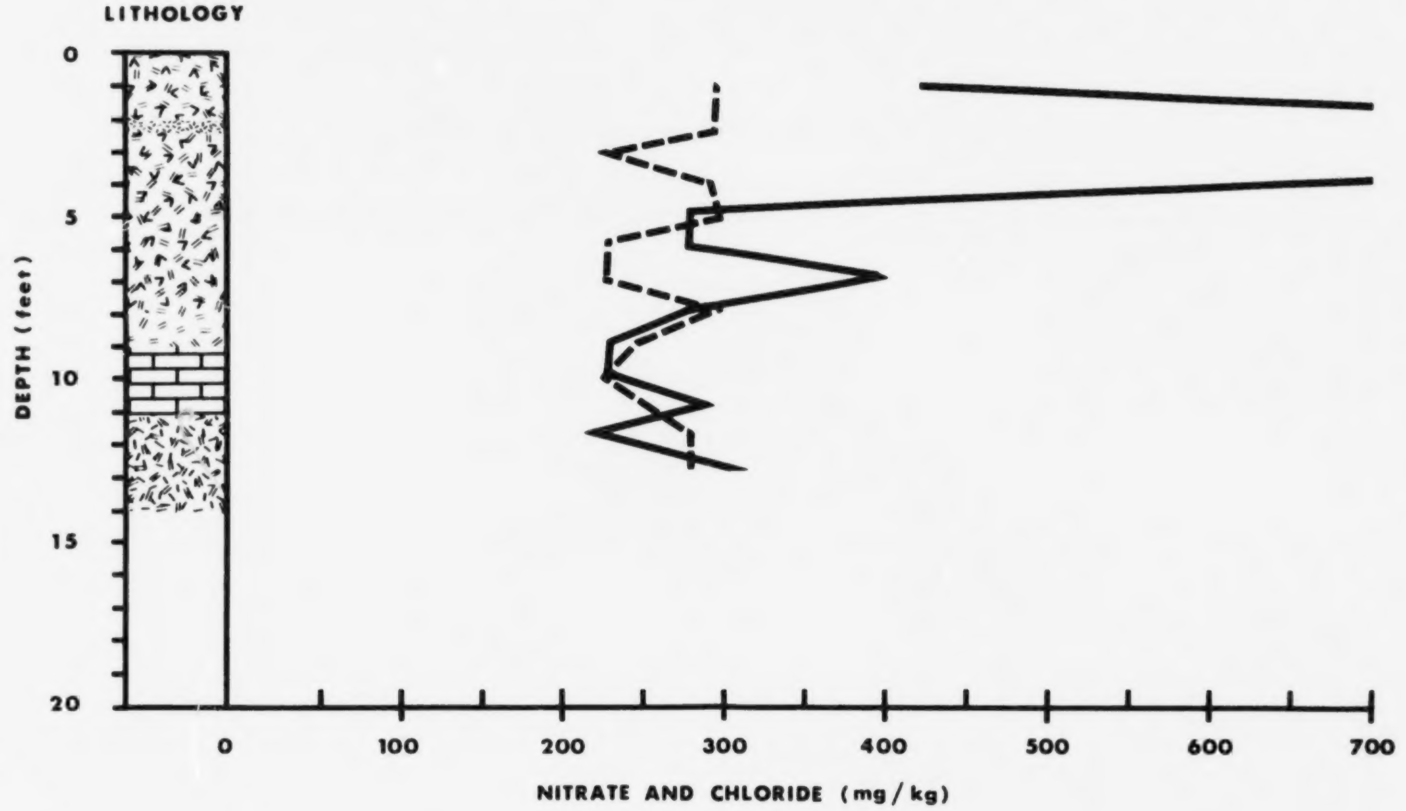
Hole 21. Located 10 feet east of well 867 (1898 ppm nitrate, 6 feet to water) and next to a water trough in a barnyard. Nitrate is very high, chloride is even higher. 1740 #/acre-foot.



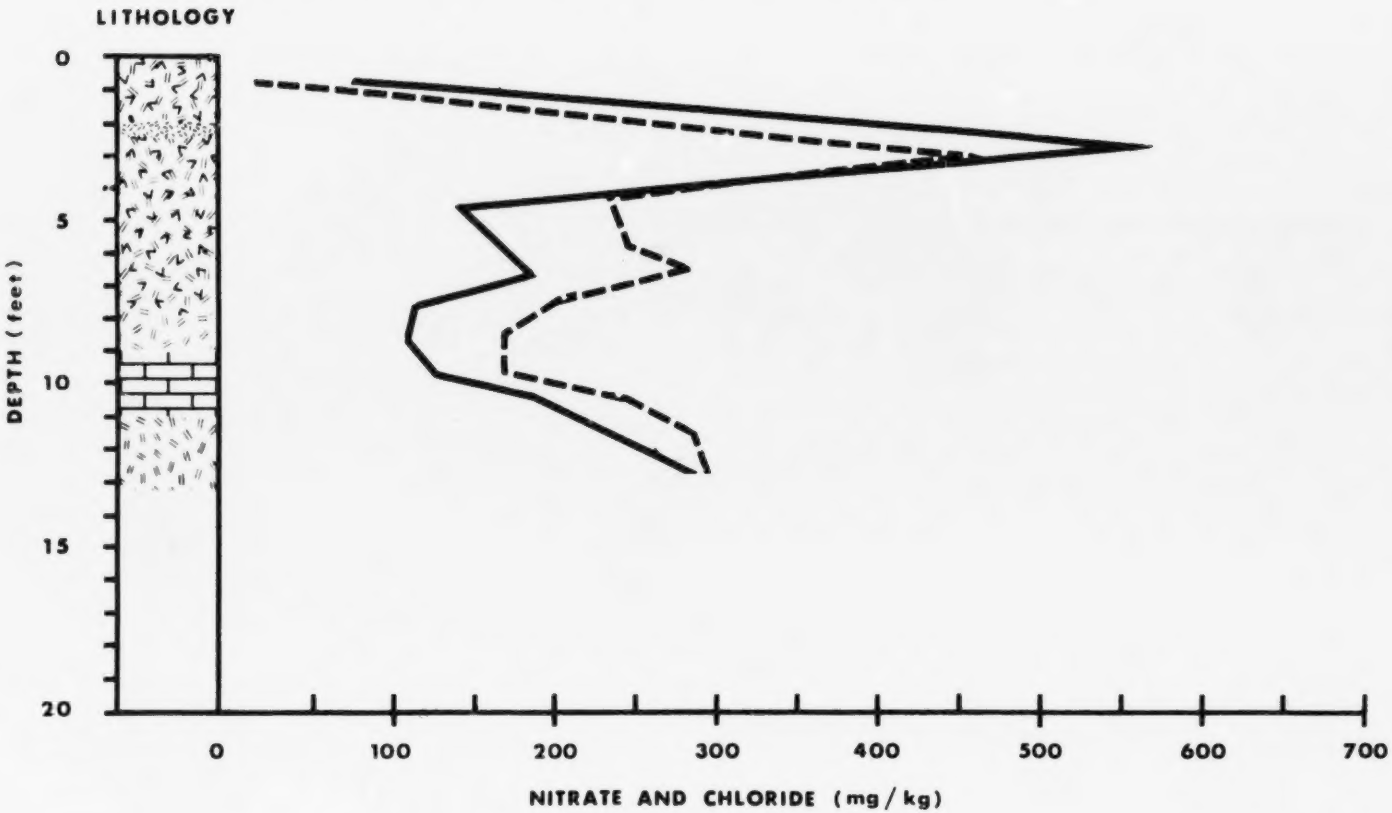
Hole 22. Located 20 feet east of well 867 (1898 ppm nitrate, 6 feet to water) in a barnyard. Very high nitrate and chloride. 2000 #/acre-foot.



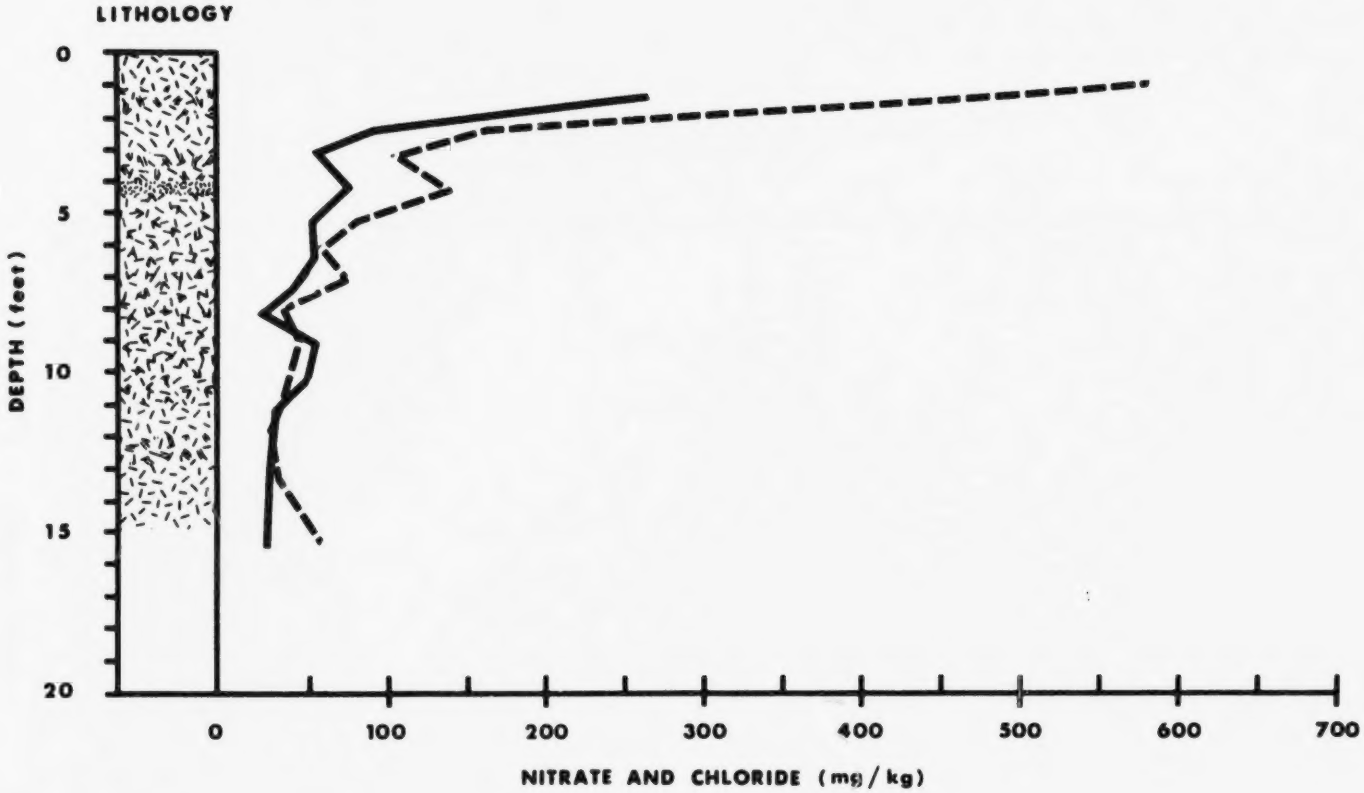
Hole 23. Located 30 feet east of well 867 (1898 ppm, 6 feet to water) and 5 feet outside a barnyard. High nitrate and chloride. 1067 #/acre-foot.



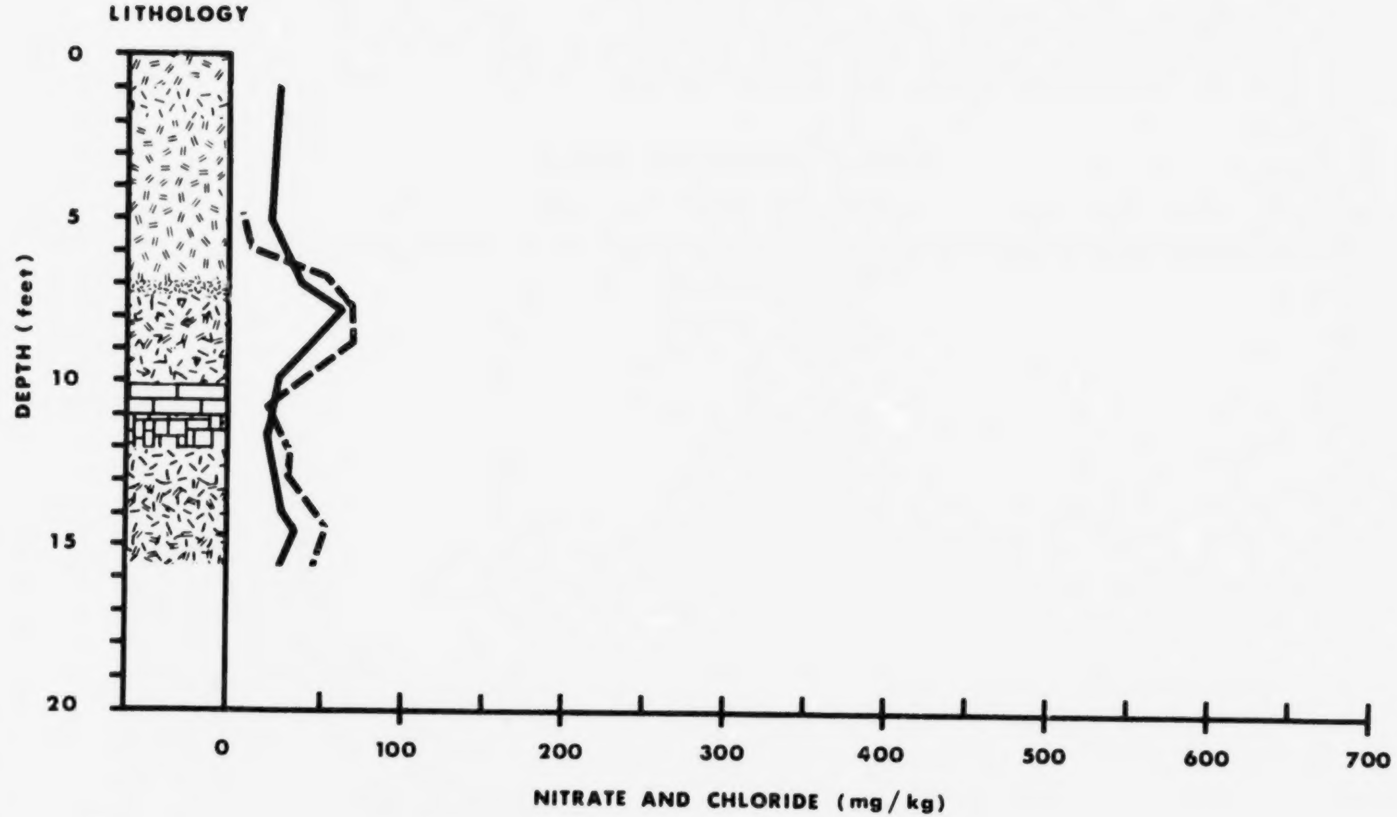
Hole 24. Located 2 feet south of a septic tank lateral and 55 feet northeast of well 867 (1898 ppm nitrate, 6 feet to water). High nitrate and chloride. 2133 #/acre-foot.



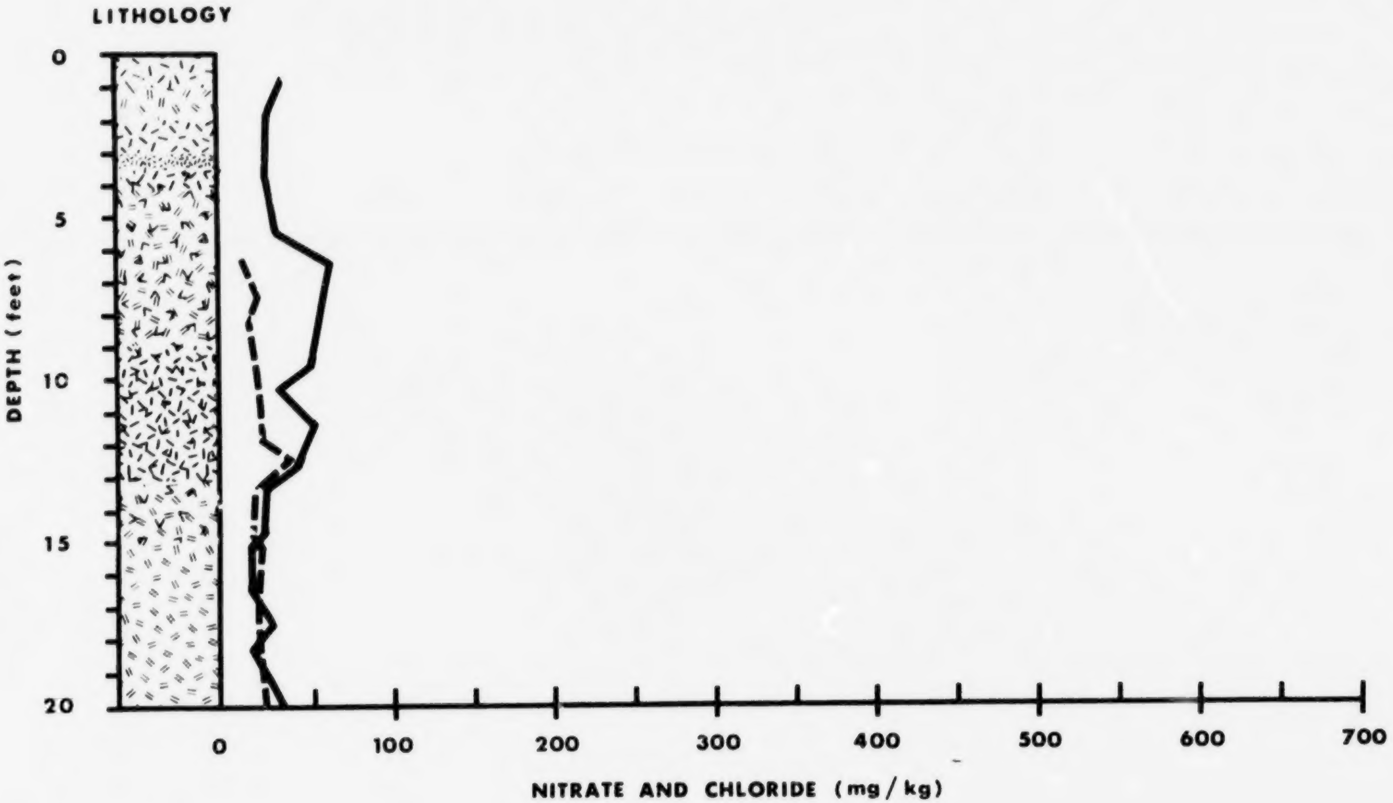
Hole 25. Located 2 feet east of a septic tank lateral, 10 feet south of hole 24, and 50 feet northeast of well 867 (1898 ppm nitrate, 6 feet to water). High nitrate and chloride. 1067 #/acre-foot.



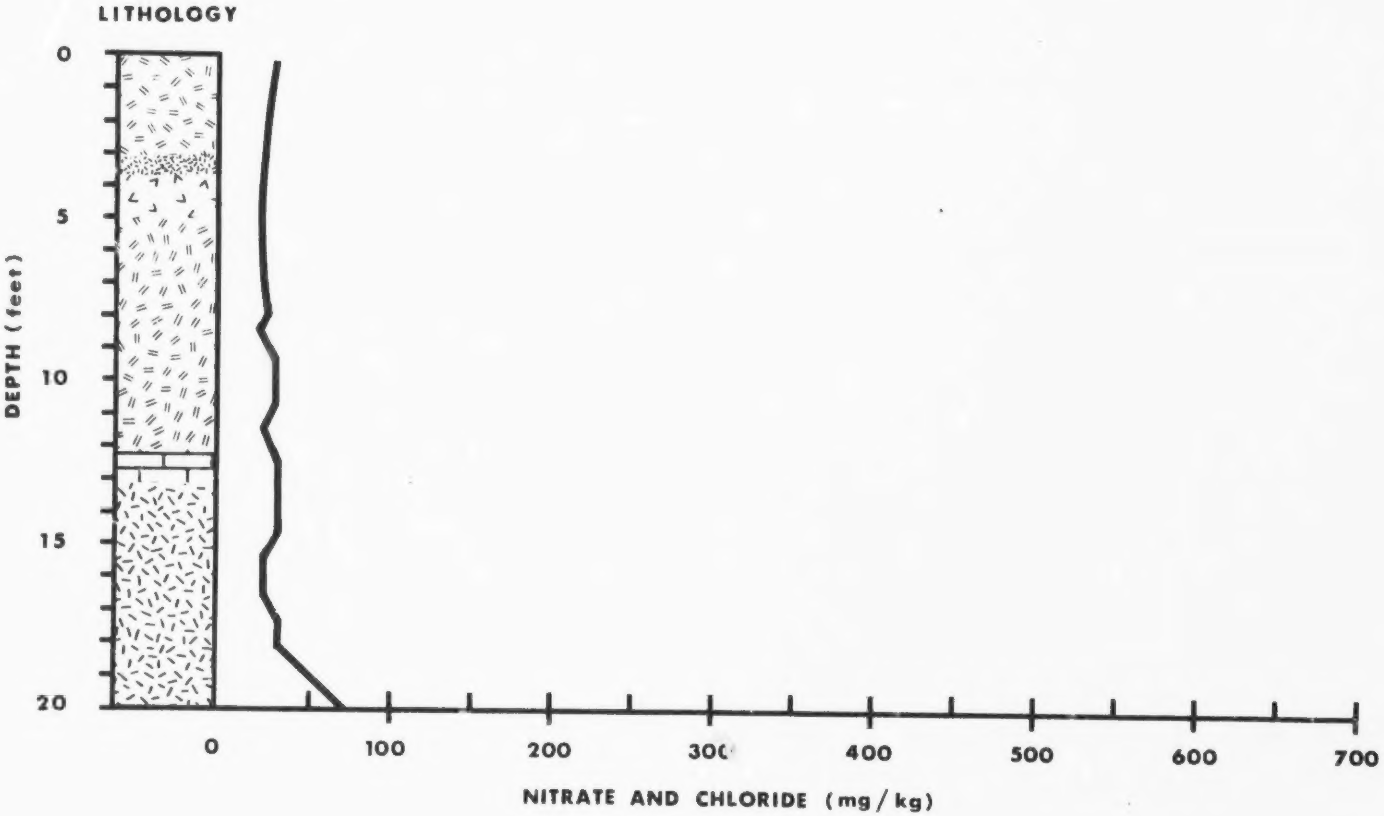
Hole 26. Located ¼ mile southeast of well 867 (1898 ppm nitrate, 6 feet to water) in a seep area in a cotton field. No history of cattle or fertilizer at this site. As expected for a seep, nitrate and chloride are high near the surface. 400 #/acre-foot.



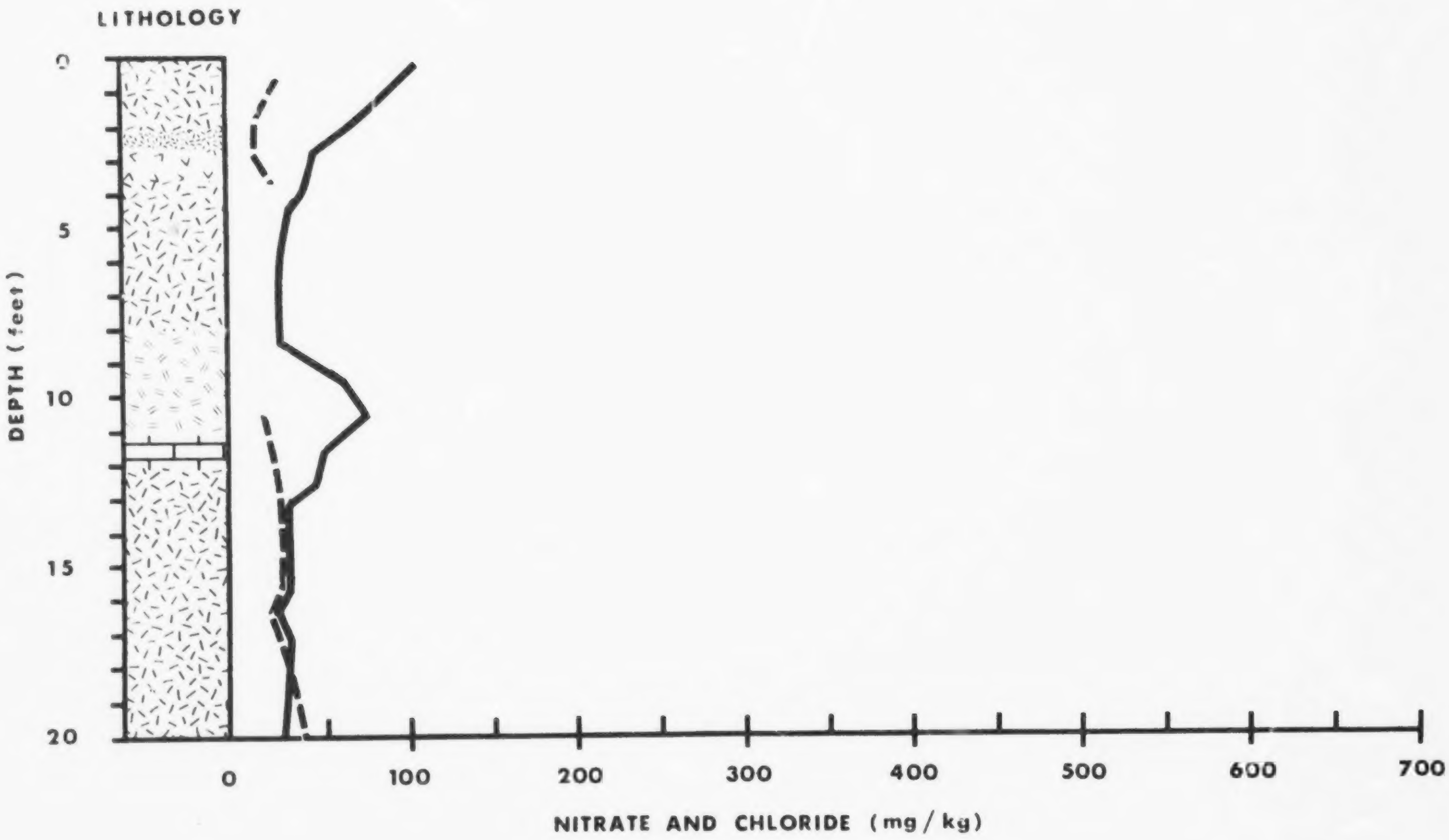
Hole 27. Located ¼ mile southwest of well 867 (1898 ppm nitrate, 6 feet to water) in a cornfield. No history of livestock or fertilizer. Nitrate and chloride are fairly low, but correlate well. 213 #/acre-foot.



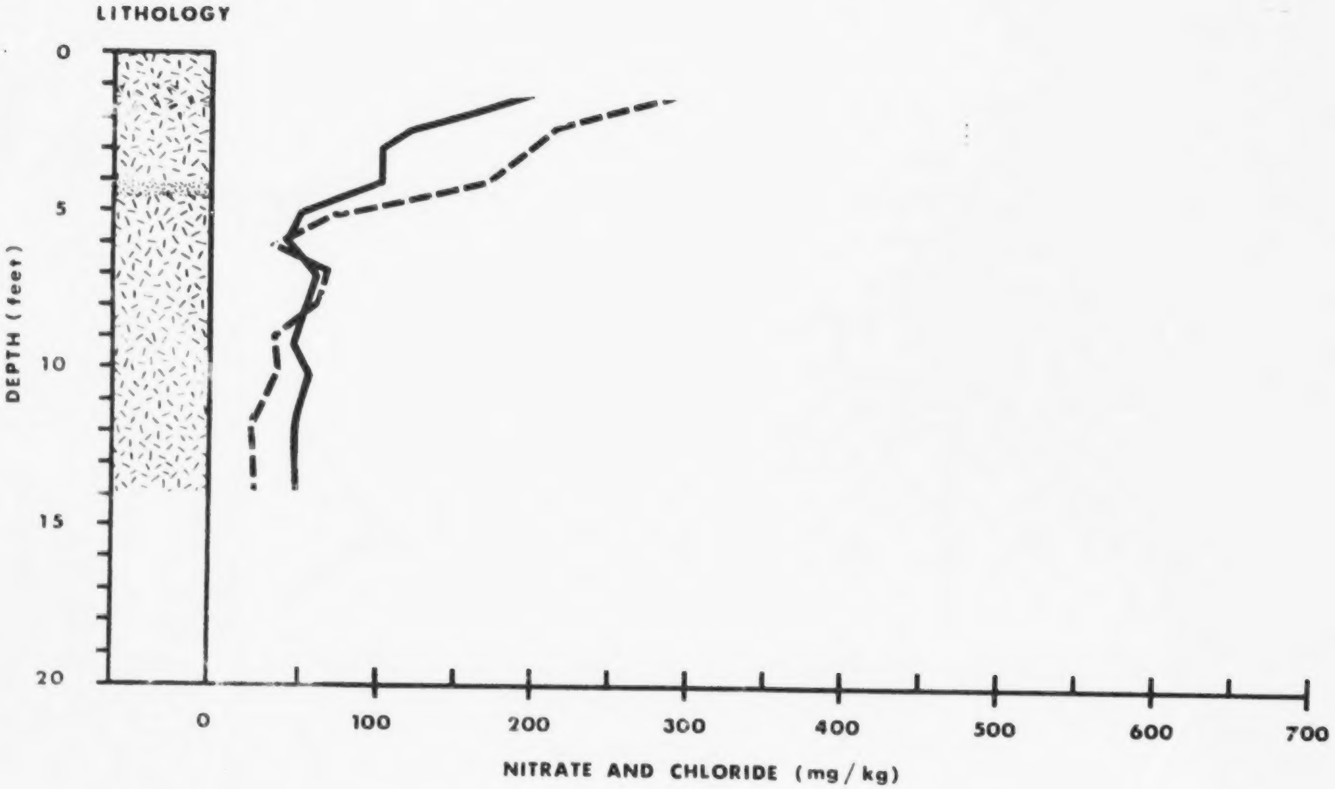
Hole 28. Located ½ mile northwest of well 393 (168 ppm nitrate, 27 feet to water) in a cotton field. Chloride is low, nitrate is fairly low. No history of cattle or fertilizer. 253 #/acre-foot.



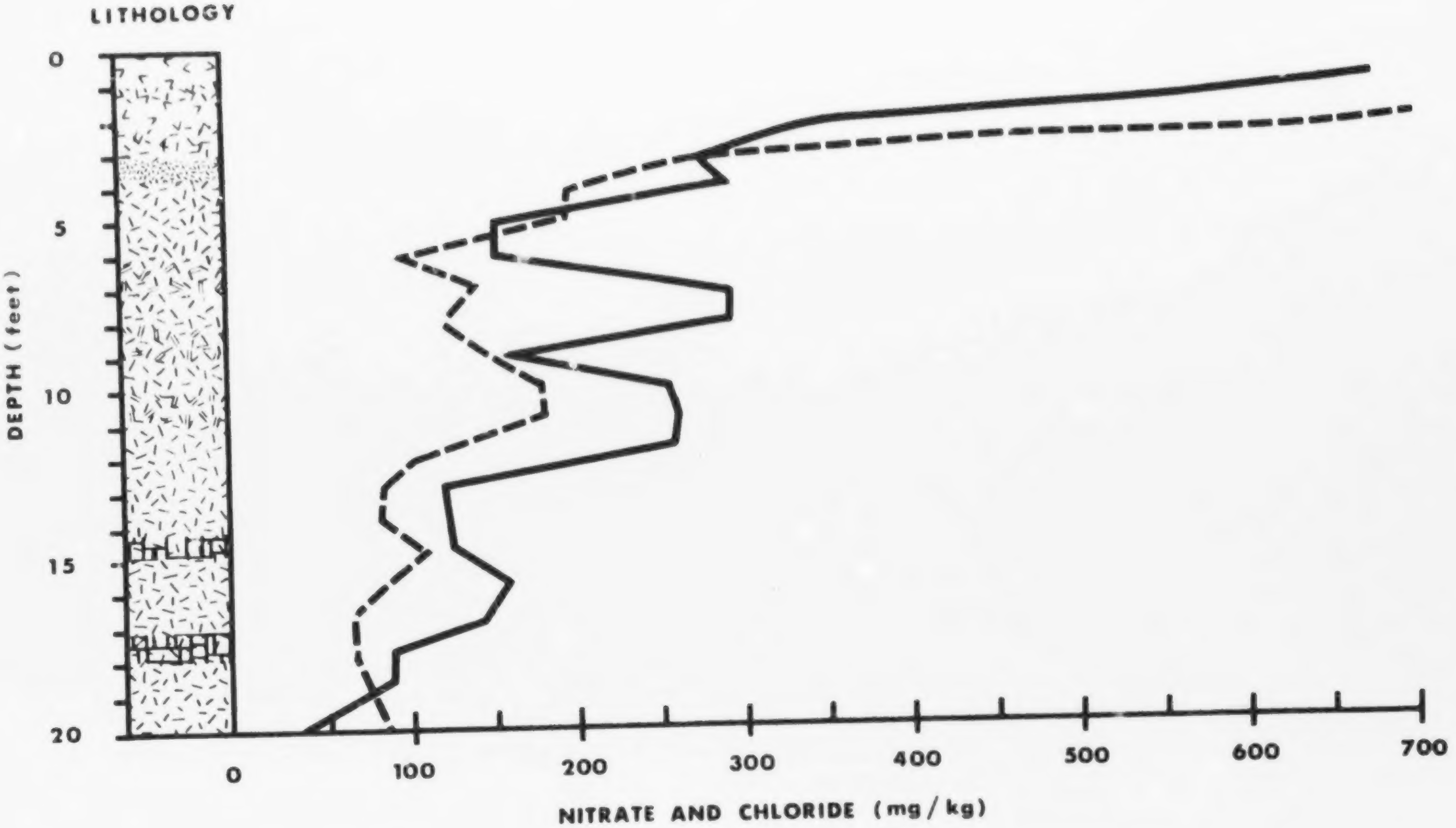
Hole 29. Located 200 feet south of well 324 (260 ppm nitrate, 44 feet to water) in a fallow field. No history of livestock or fertilizer. Nitrate is low, chloride is very low. 160 #/acre-foot.



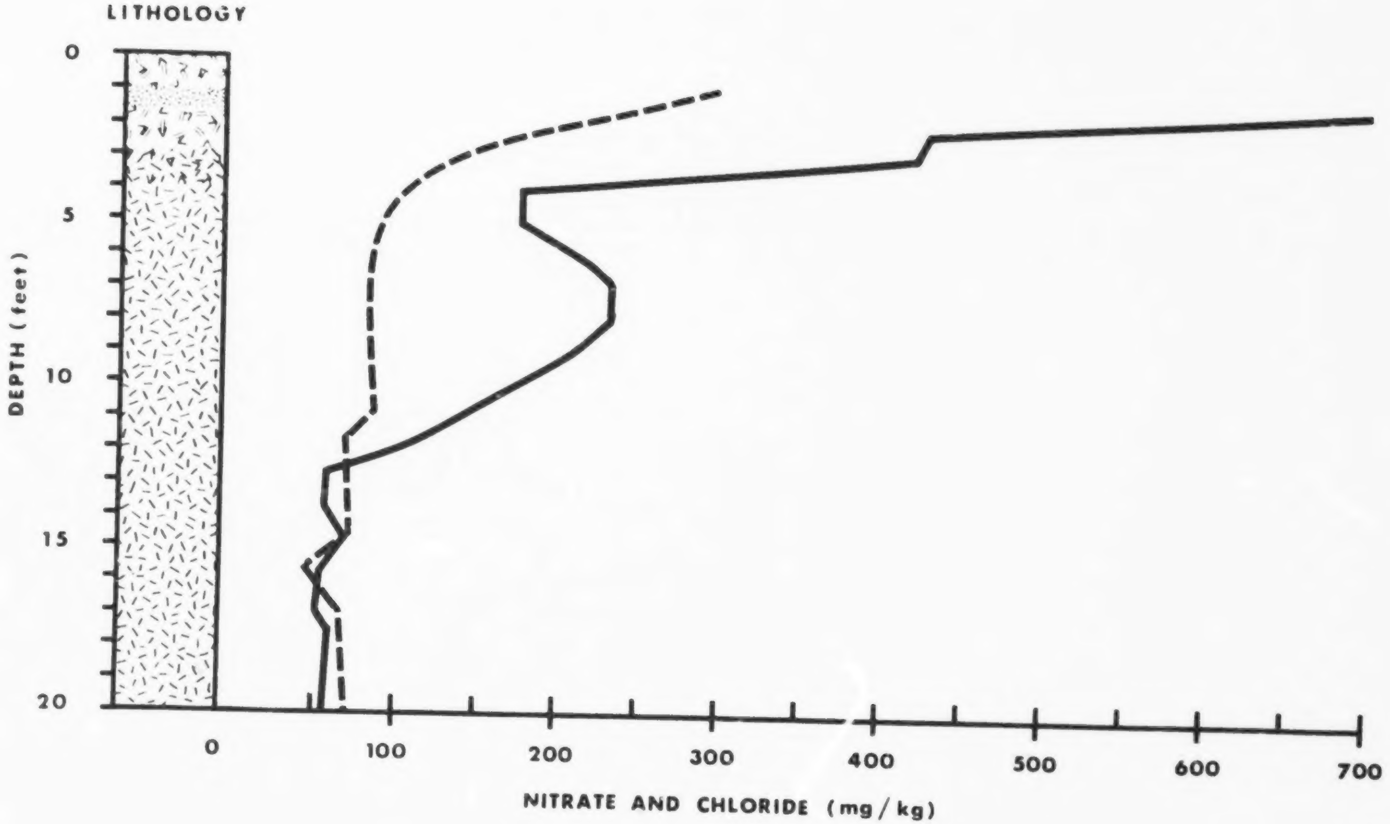
Hole 30. Located at the Lange Drilling Company in the town of Rowena. Low chloride and fairly low nitrate. 293 #/acre-foot.



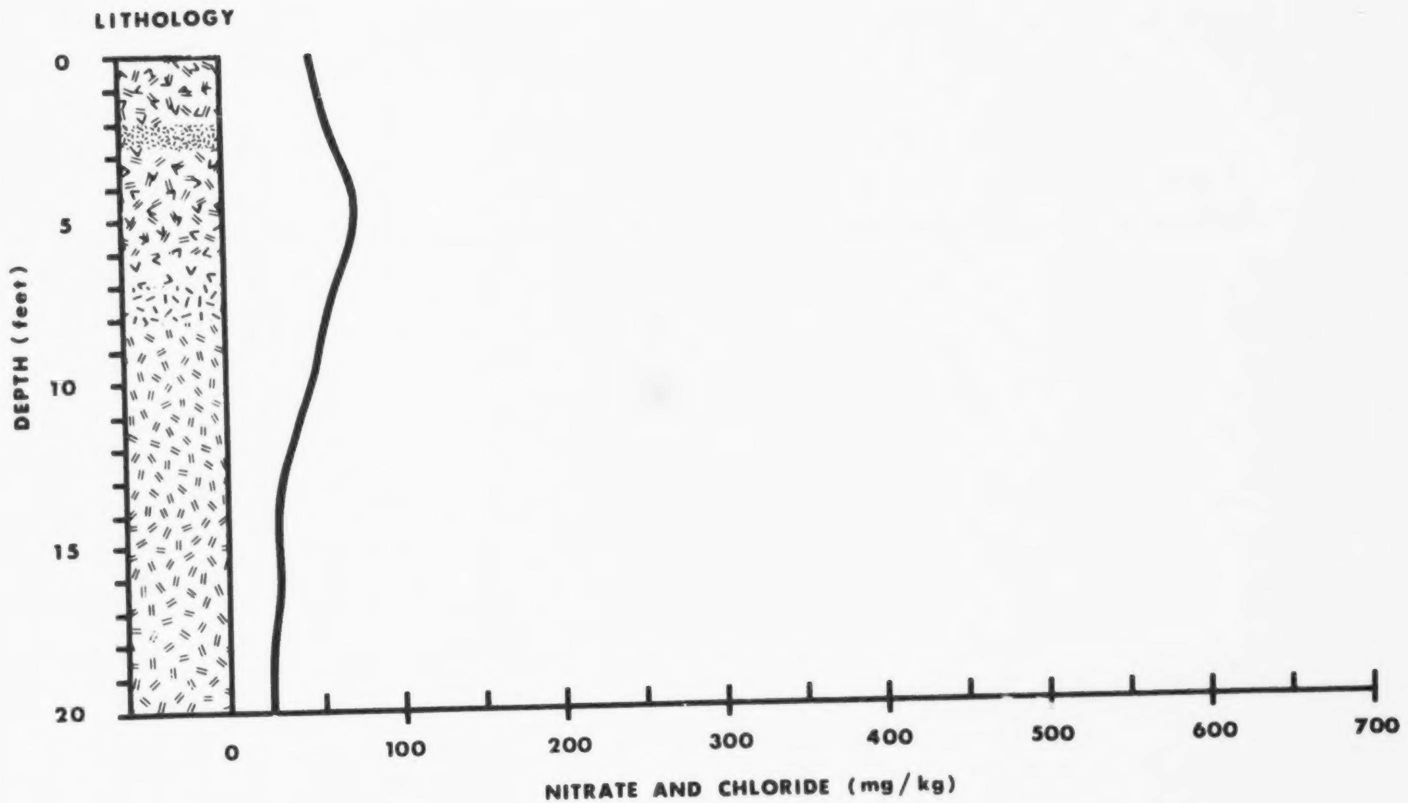
Hole 31. Located 50 feet northwest of well 728 (130 ppm nitrate, 6 feet to water) in an old stream bed, now a seep area. Cattle have grazed on fertilized bermuda grass at this site. Nitrate and chloride correlate well, and are higher near the surface as might be expected in a seep where evaporation is taking place. 393 #/acre-foot.



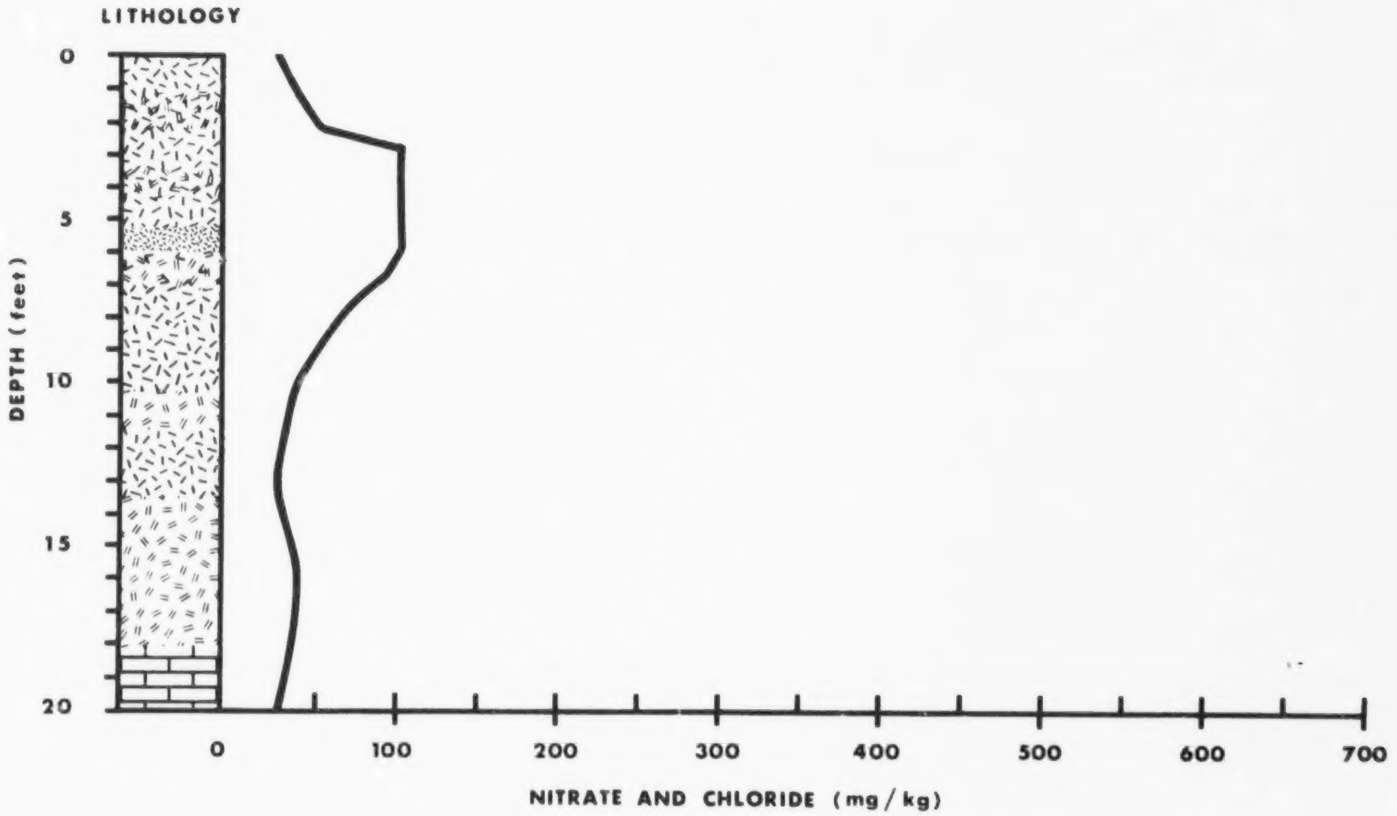
Hole 32. Located 30 feet west of well 727 (1260 ppm nitrate) in a corral. Nitrate and chloride correlate well and are very high. 1540 #/acre-foot.



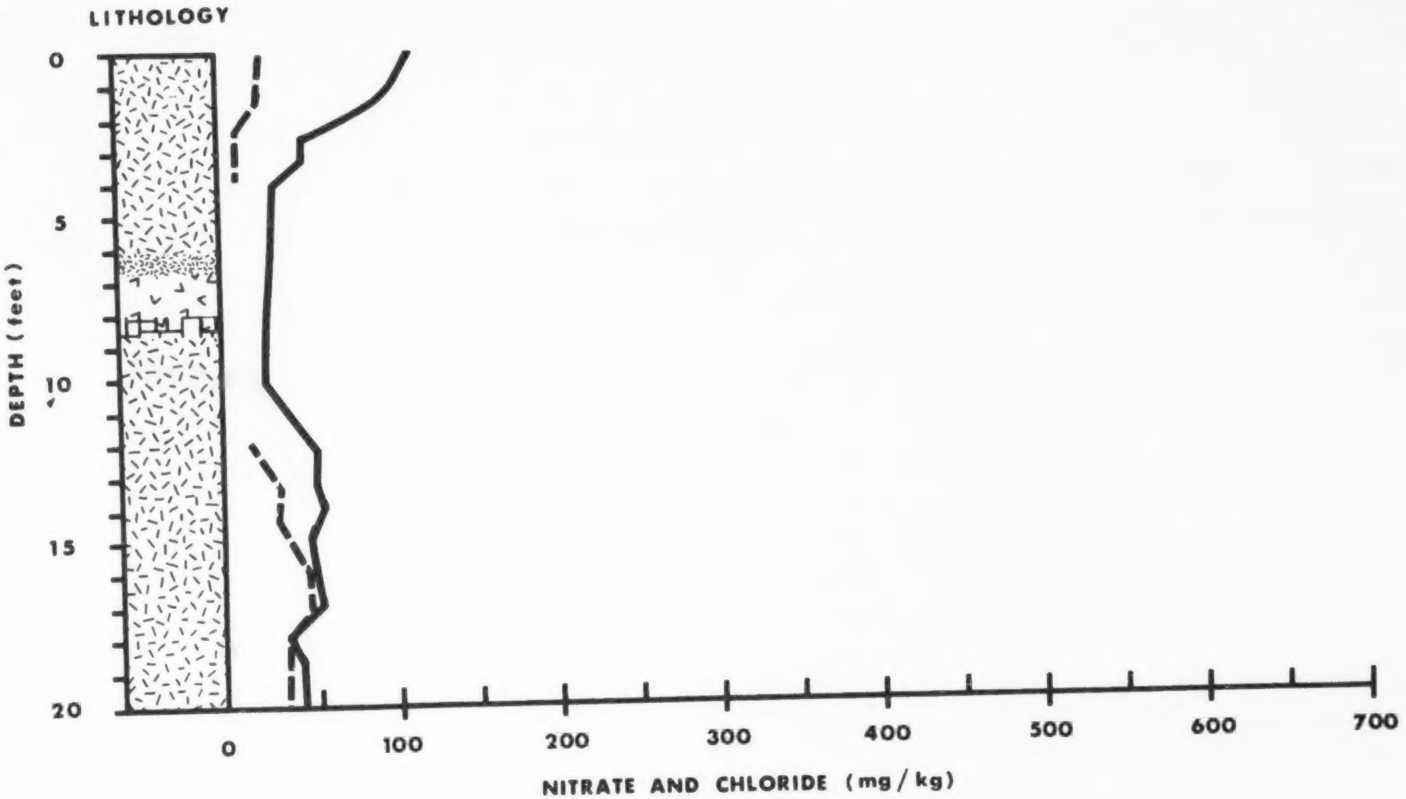
Hole 33. Located ¼ mile south of well 1002 (280 ppm nitrate, 4 feet to water) on old farm site. Now a seep area in a cotton field. Nitrate is very high, chloride is high. 1340 #/acre-foot.



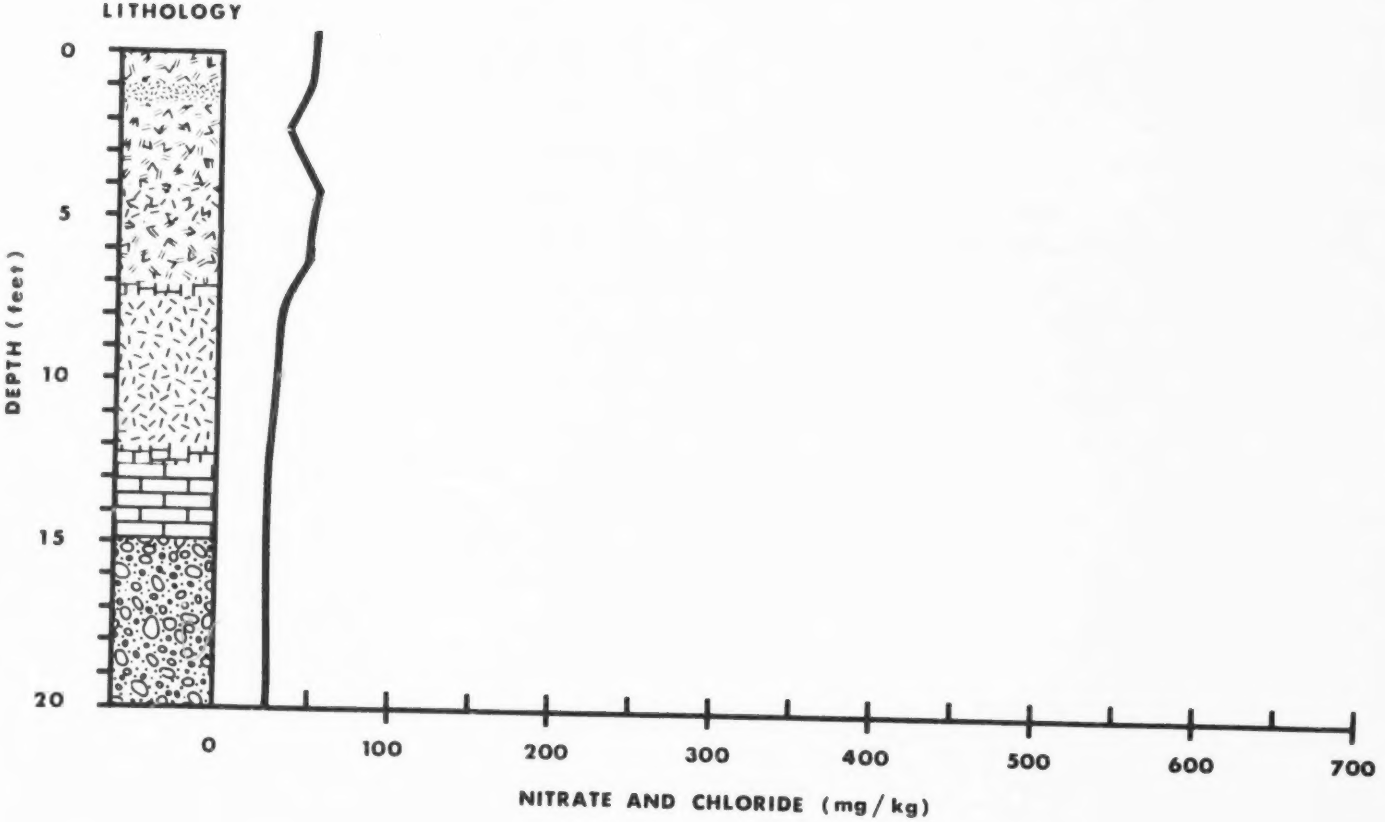
Hole 34. Located 200 feet east of well 202 (90 ppm nitrate, 0 feet to water) in a cotton field. No history of livestock or fertilizer. Chloride is very low, nitrate is fairly high. 353 #/acre-foot.



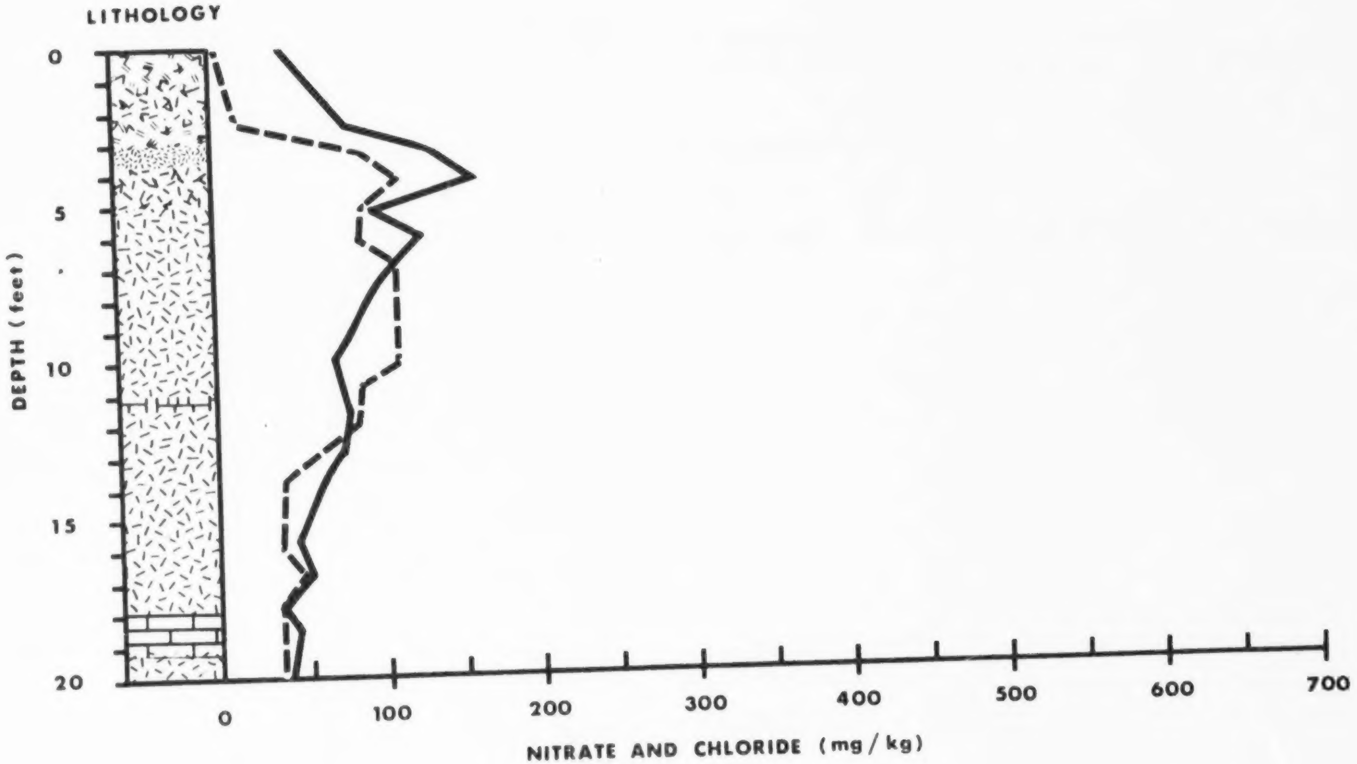
Hole 35. Located 30 feet northeast of well 1001 (190 ppm nitrate) in a cotton field. No history of fertilizer or livestock. Nitrate is high, chloride is very low. 387 #/acre-foot.



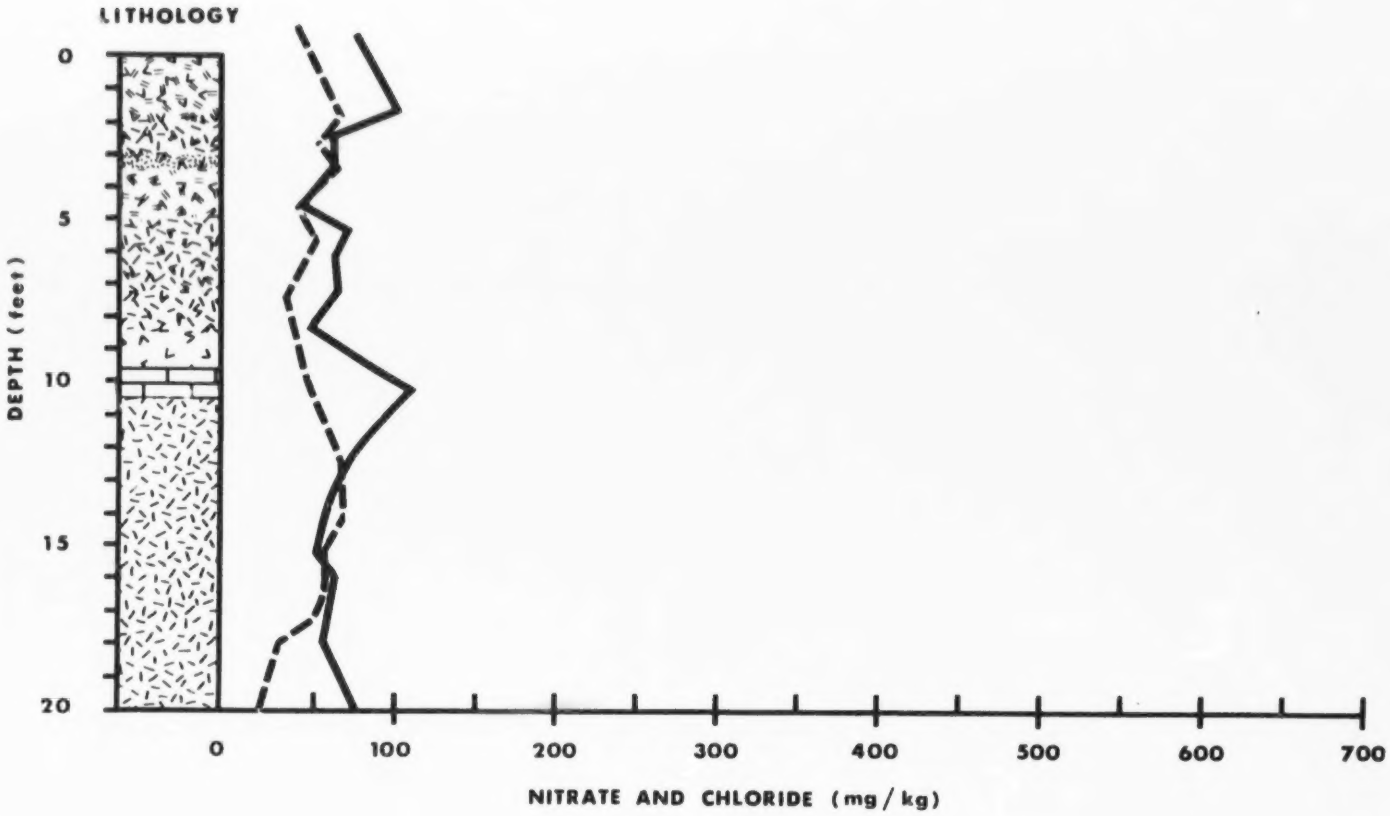
Hole 36. Located ¼ mile north of well 365 (64 ppm nitrate). No history of livestock or fertilizer. Nitrate and chloride are fairly low. 260 #/ acre-foot.



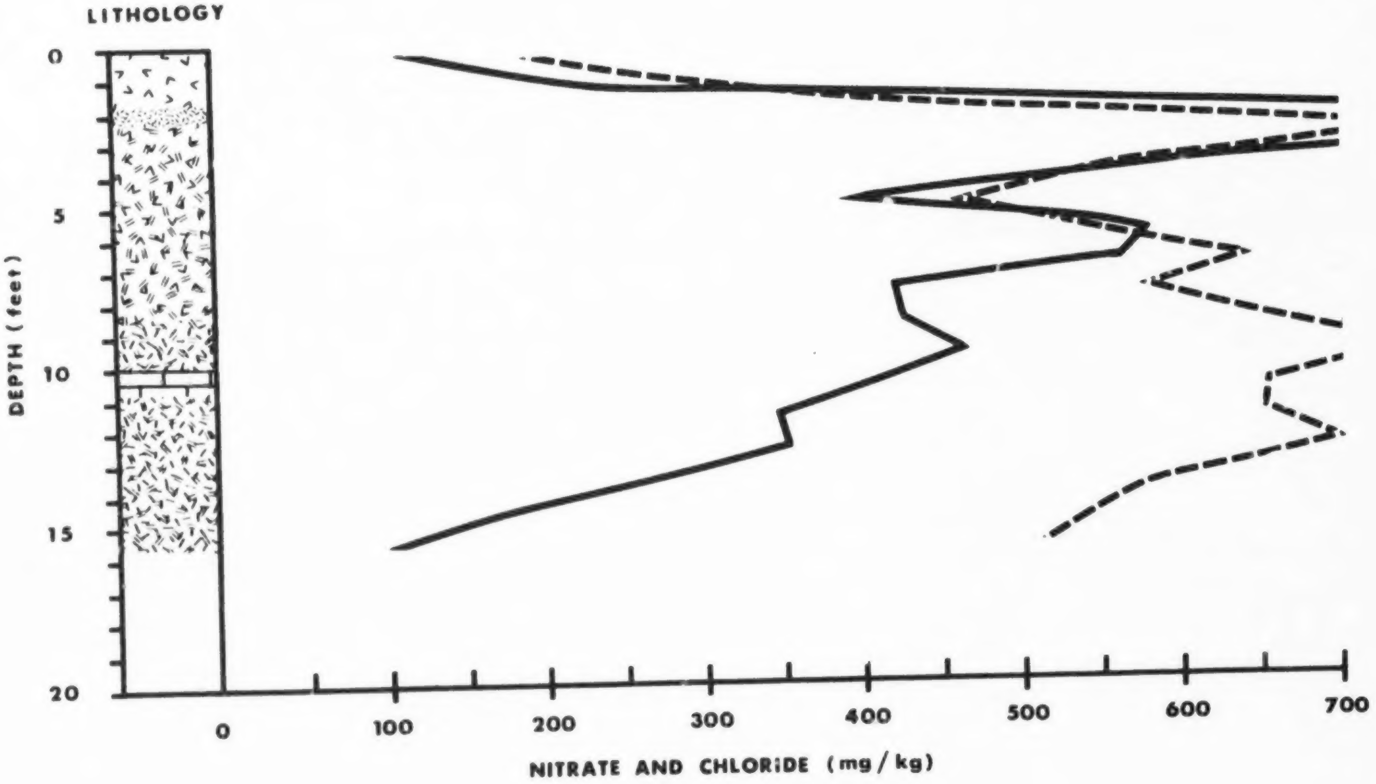
Hole 37. Located ½ mile west of well 141 (220 ppm nitrate) in a pasture where cattle are raised. Chloride is very low, nitrate is fairly low. 247 #/acre-foot.



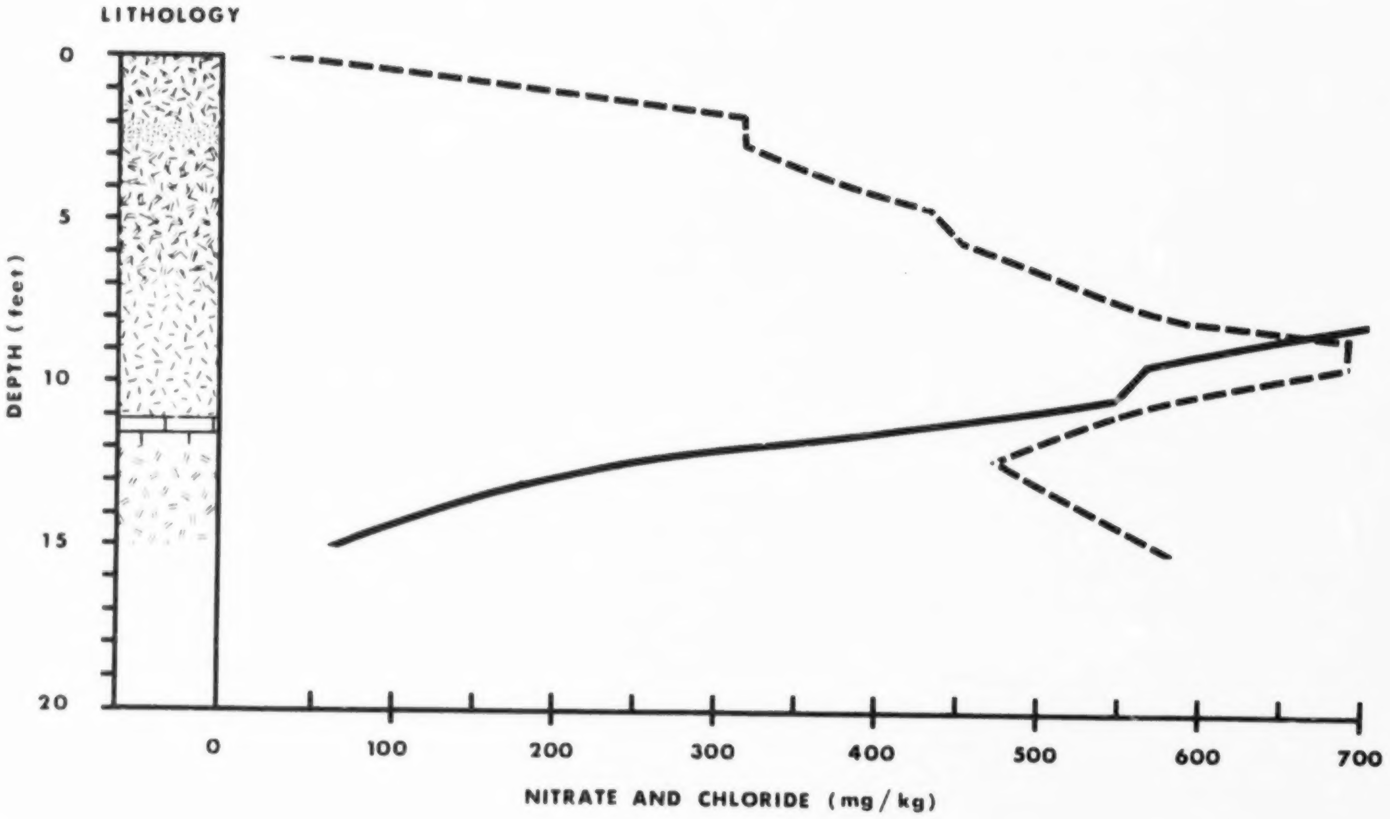
Hole 38. Located ¼ mile southwest of well 551 (294 ppm nitrate, 56 feet to water), next to a seep area in a cotton field. This is near the site of a deserted farm complex. Nitrate and chloride are fairly high and correlate well.



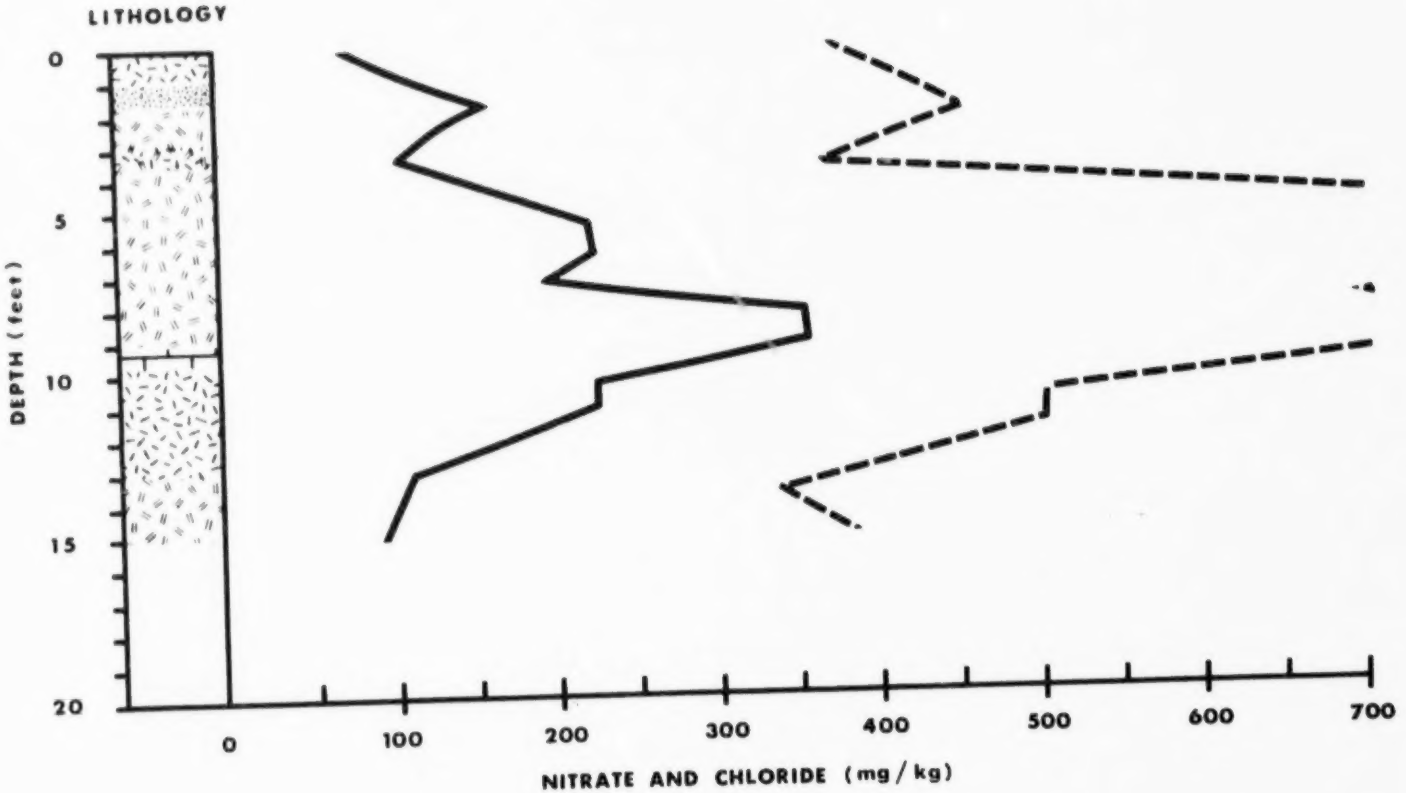
Hole 39. Located 5 feet north of well 551 (294 ppm nitrate, 56 feet to water) and 100 feet south of a barnyard. Nitrate and chloride are fairly high. 447 #/acre-foot.



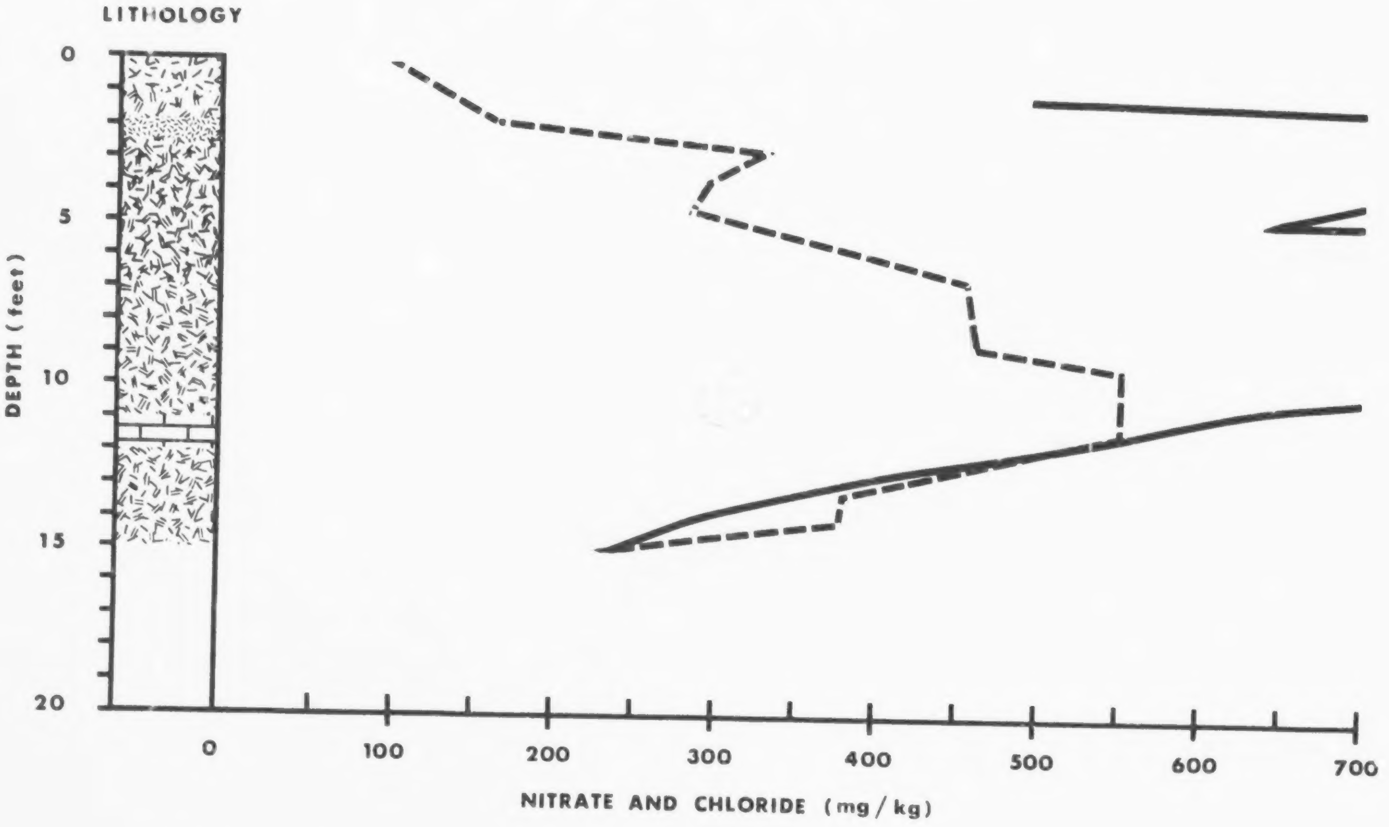
Hole 40. Located 100 feet north of well 551 (294 ppm nitrate, 56 feet to water) in a barnyard. Nitrate and chloride are very high. 2667 #/ acre-foot.



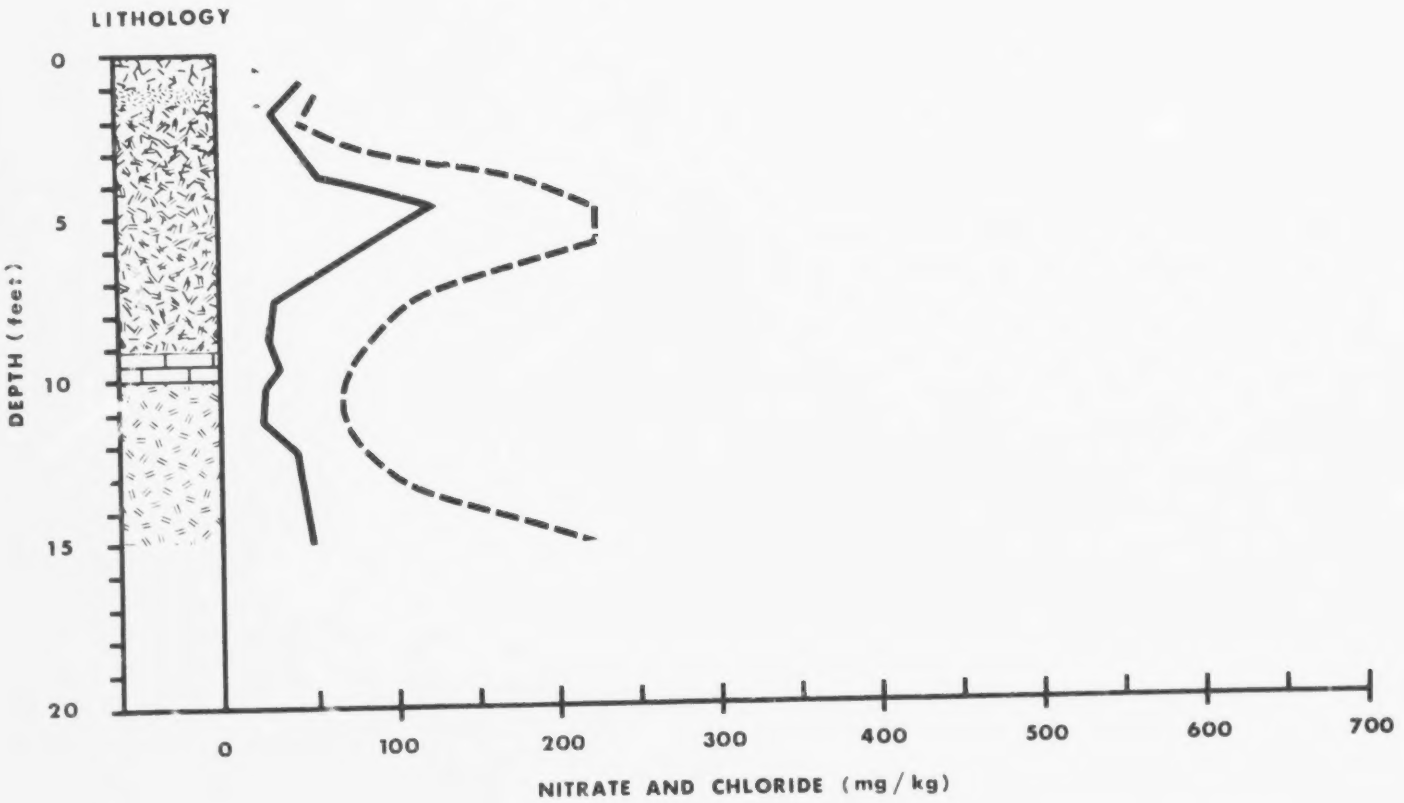
Hole 41. Located in the same barnyard as Hole 40. Extremely high nitrate and chloride. 3967 #/acre-foot.



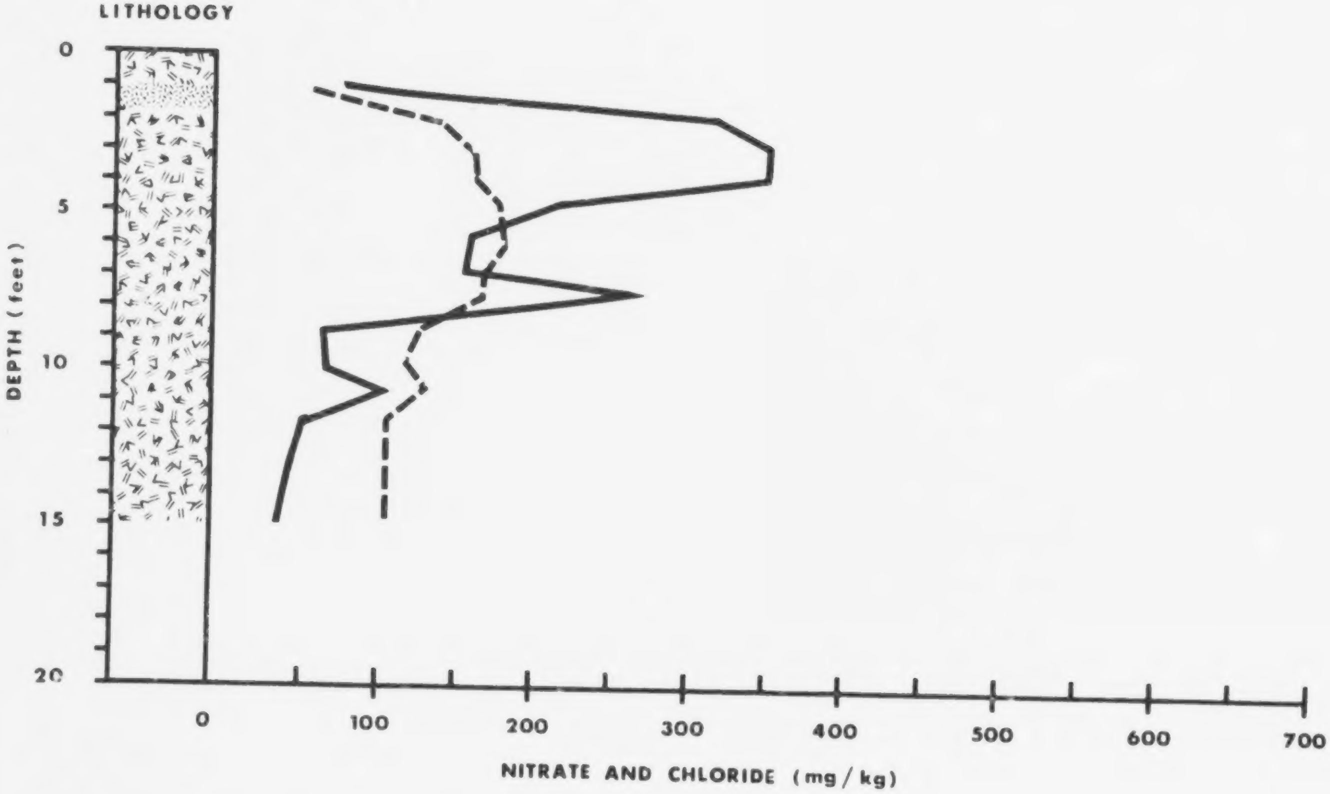
Hole 42. Located on the site of the barn of the barnyard drilled by Holes 40 and 41. Nitrate is high and chloride is extremely high. 1332 #/acre-foot.



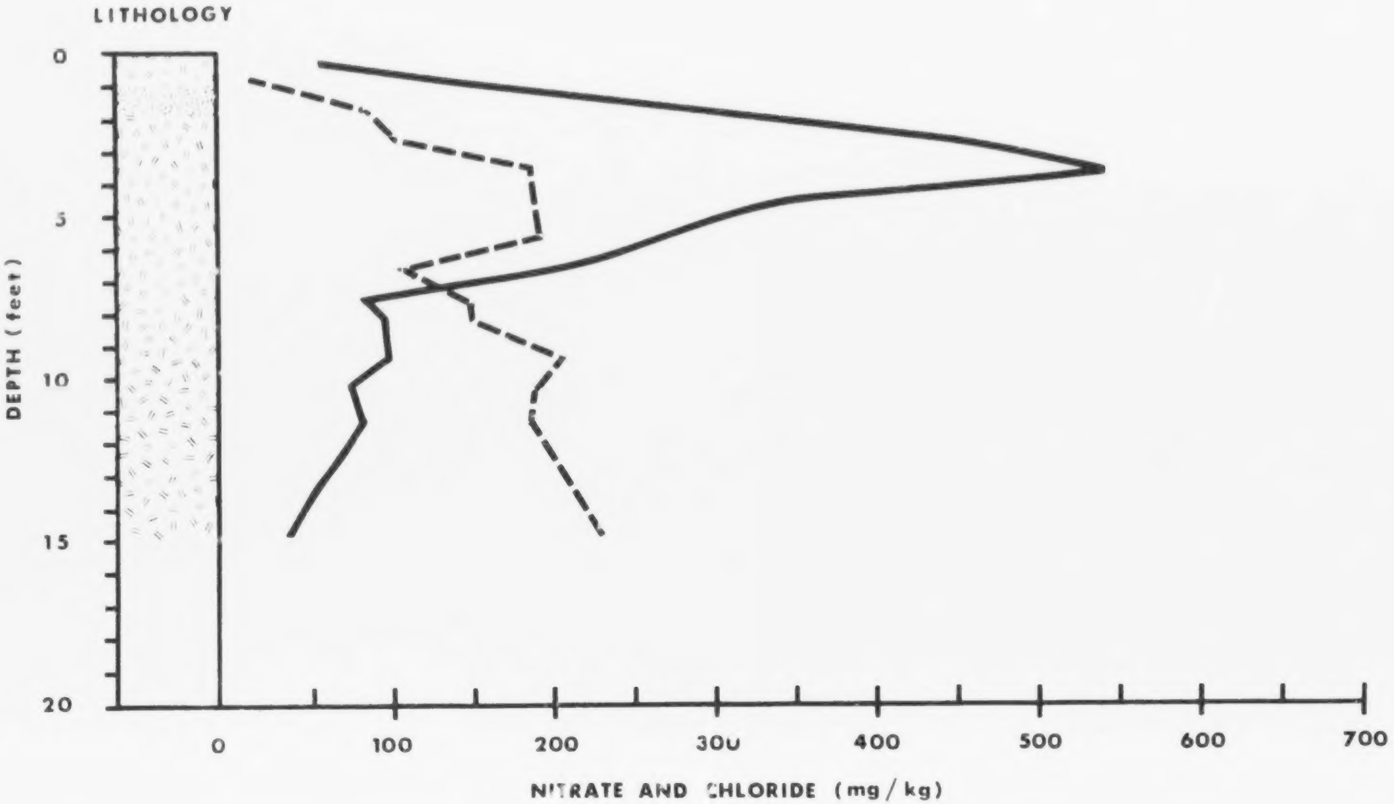
Hole 43. Located 5 feet outside the barnyard drilled by Holes 40, 41, and 42. Very high chloride, extremely high nitrate. 5267 #/ acre-foot.



Hole 44. Located 60 feet north of well 551 (294 ppm nitrate, 56 feet to water) and 10 feet north of a septic tank lateral. Chloride is high, nitrate is fairly high. 313 #/acre-foot.



Hole 45. Located 10 feet south of well 1034 (2162 ppm nitrate). This hole was drilled at the site of an old water trough where many cattle were watered in the early 1900's. No cattle have been raised here in the past 30 years. Nitrate and chloride are high at fairly shallow depths. 953 #/acre-foot.

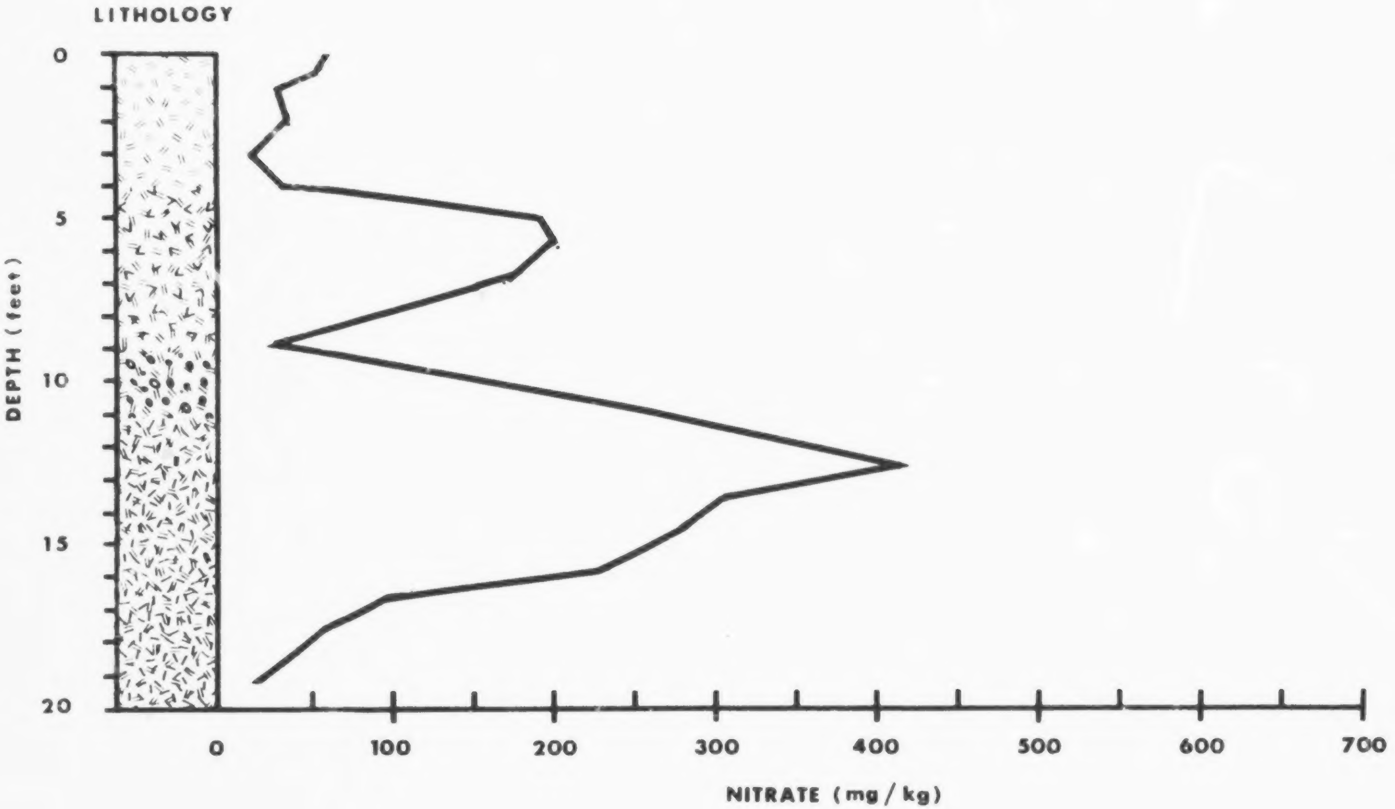


Hole 46. Located 40 feet east of well 1034 (2162 ppm nitrate) in a cotton field. Many cattle in this area in the early 1900's. Chloride is high, nitrate is very high. 1153 #/acre-foot.

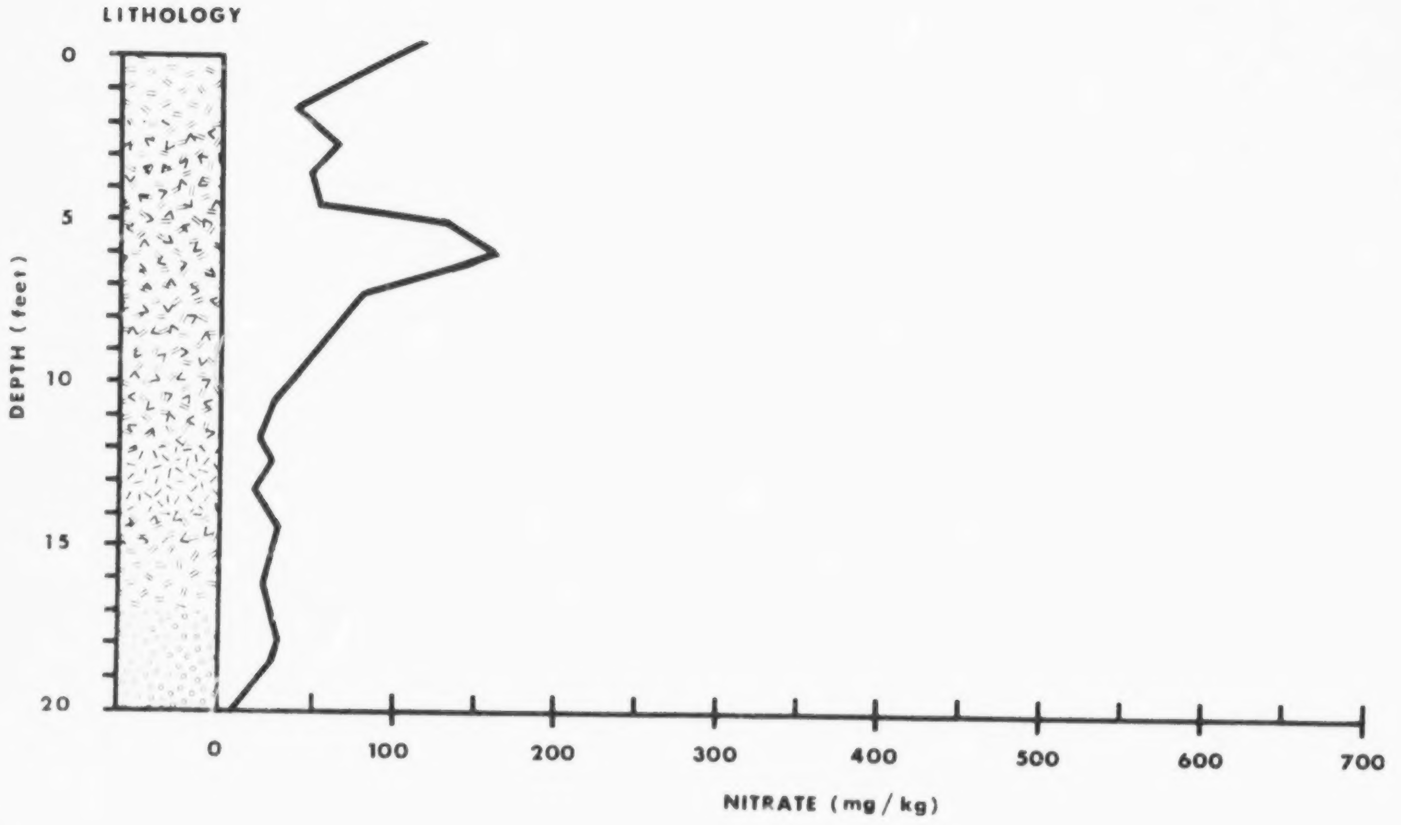
APPENDIX IV

PROFILES FOR SOIL NITRATE

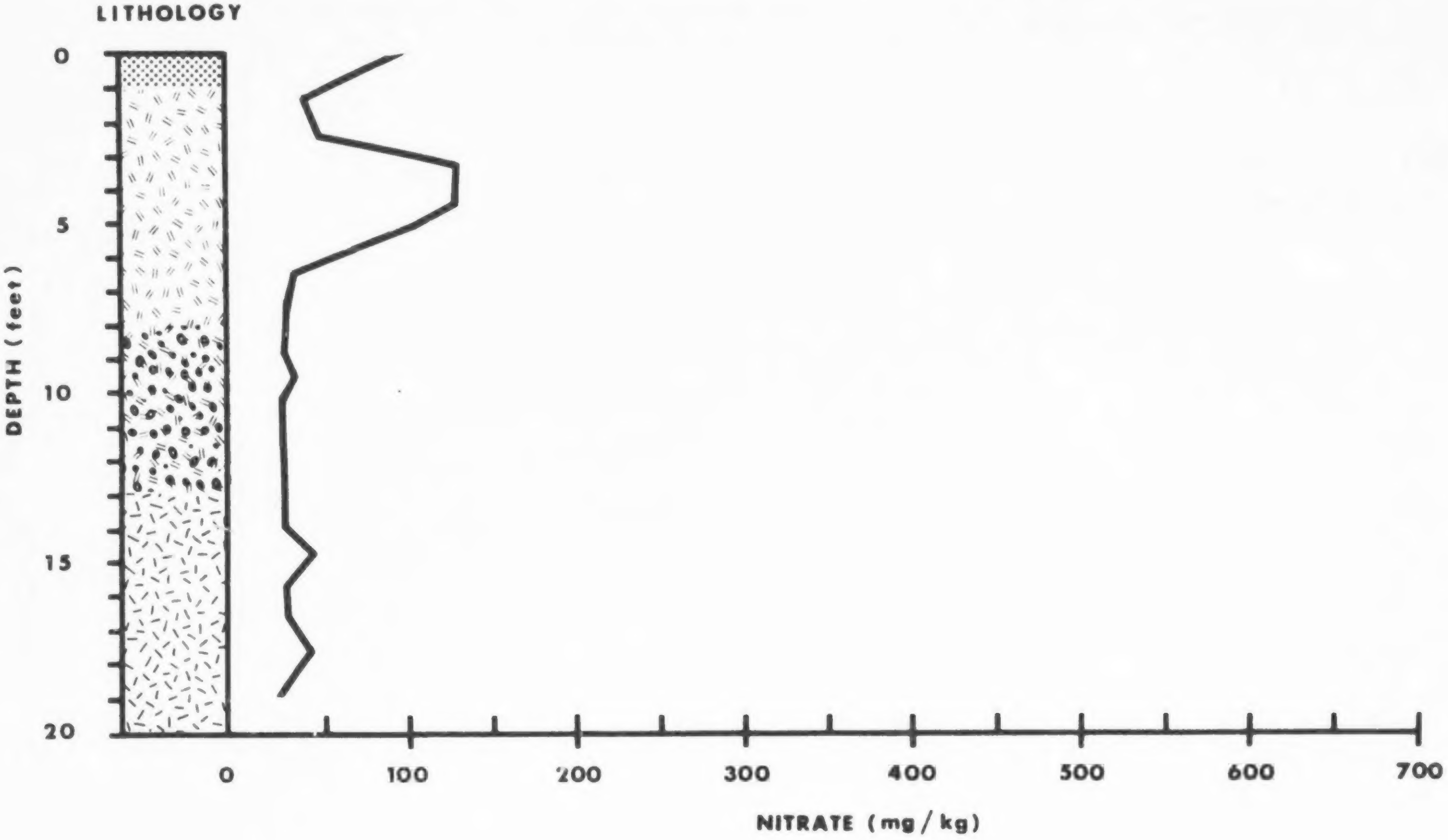
For Index to Lithology
See Page 129



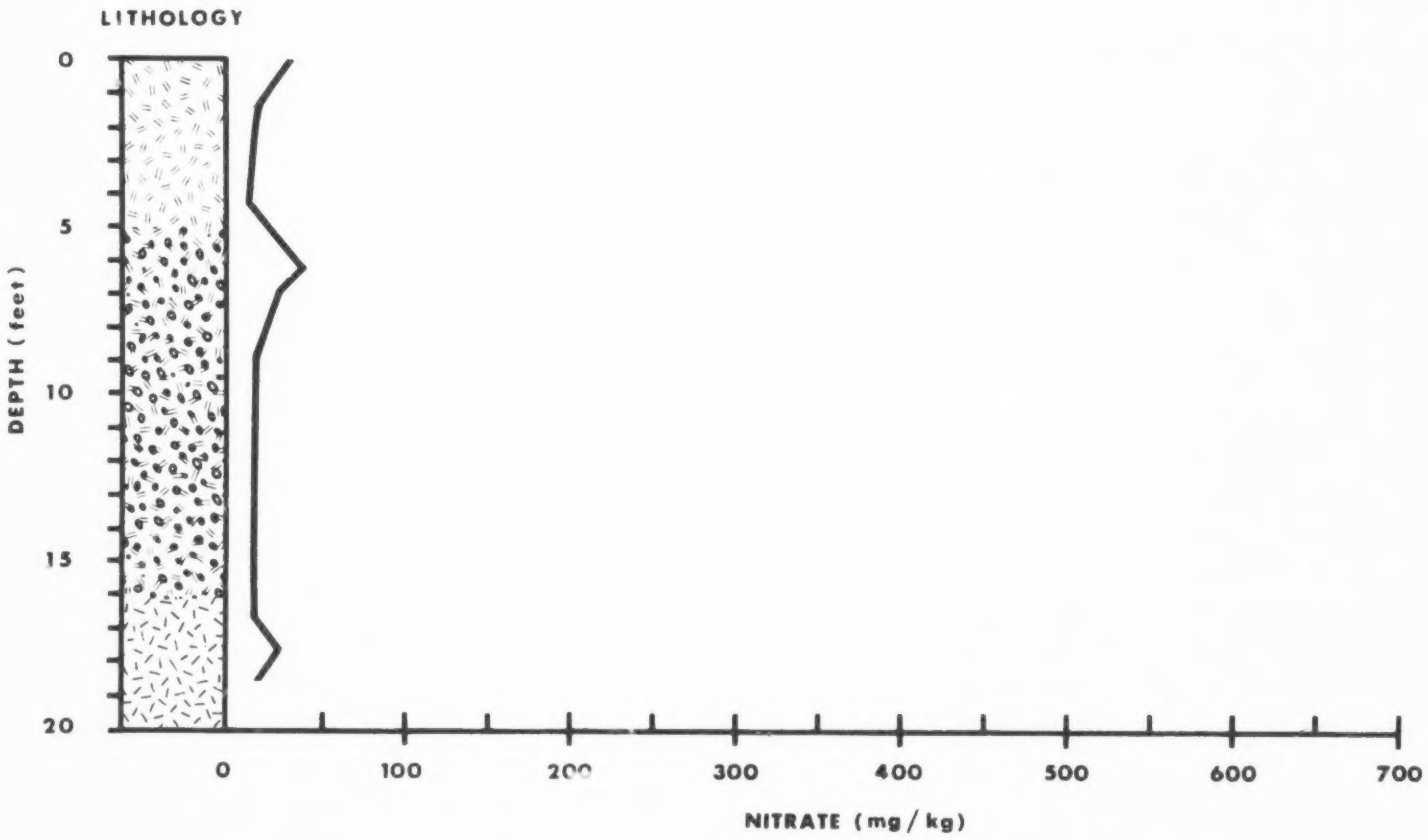
Hole 47. Located 100 feet west of well 608 (504 ppm nitrate, 35 feet to water) next to a deserted farmhouse. Nitrate is very high. There was no barnyard at this house. 1,150 #/acre-foot.



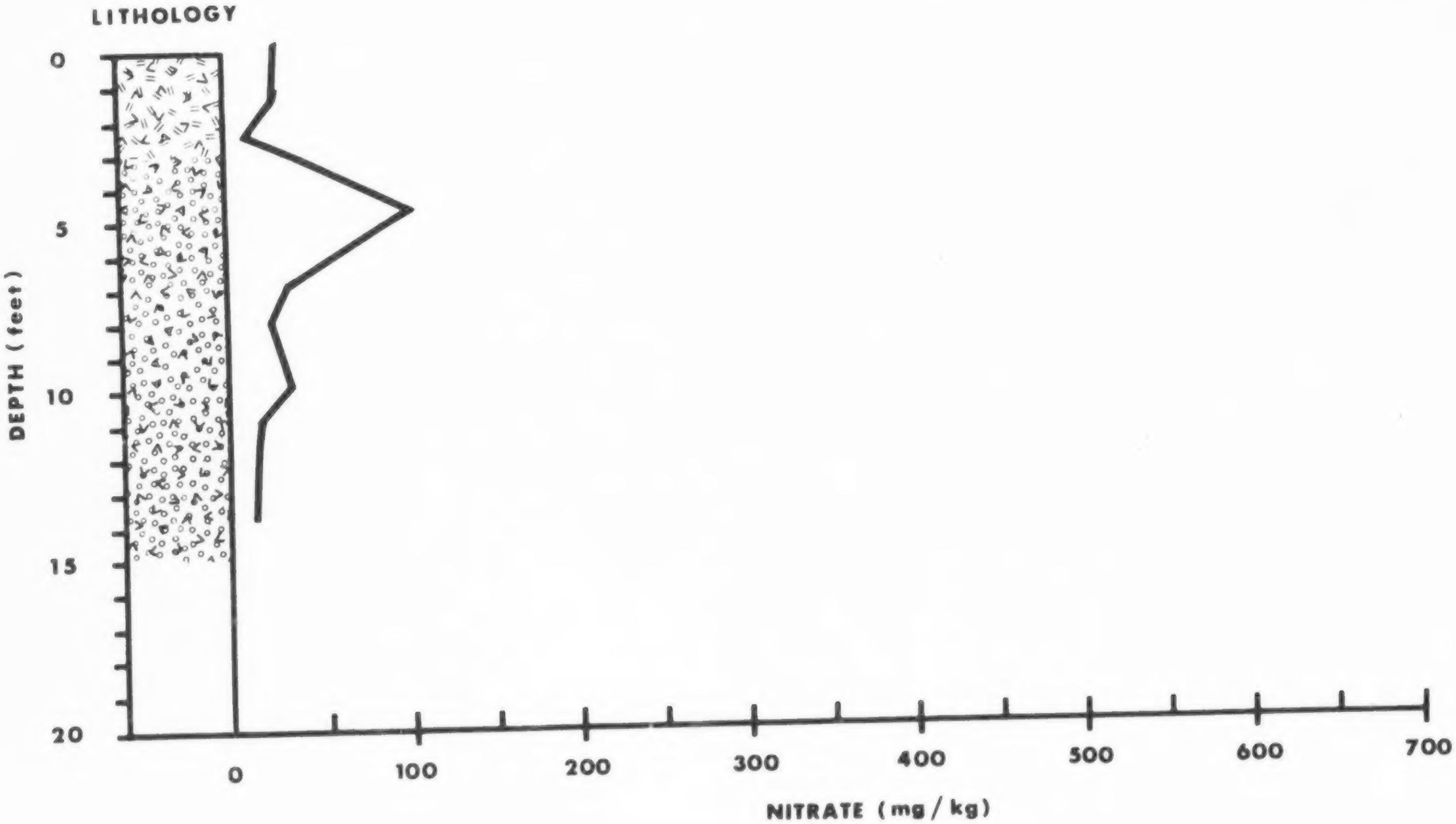
Hole 48. Located 700 feet north of well 608 (504 ppm nitrate, 35 feet to water) in a cotton field next to a road. Nitrate is high. 345 #/ acre-foot.



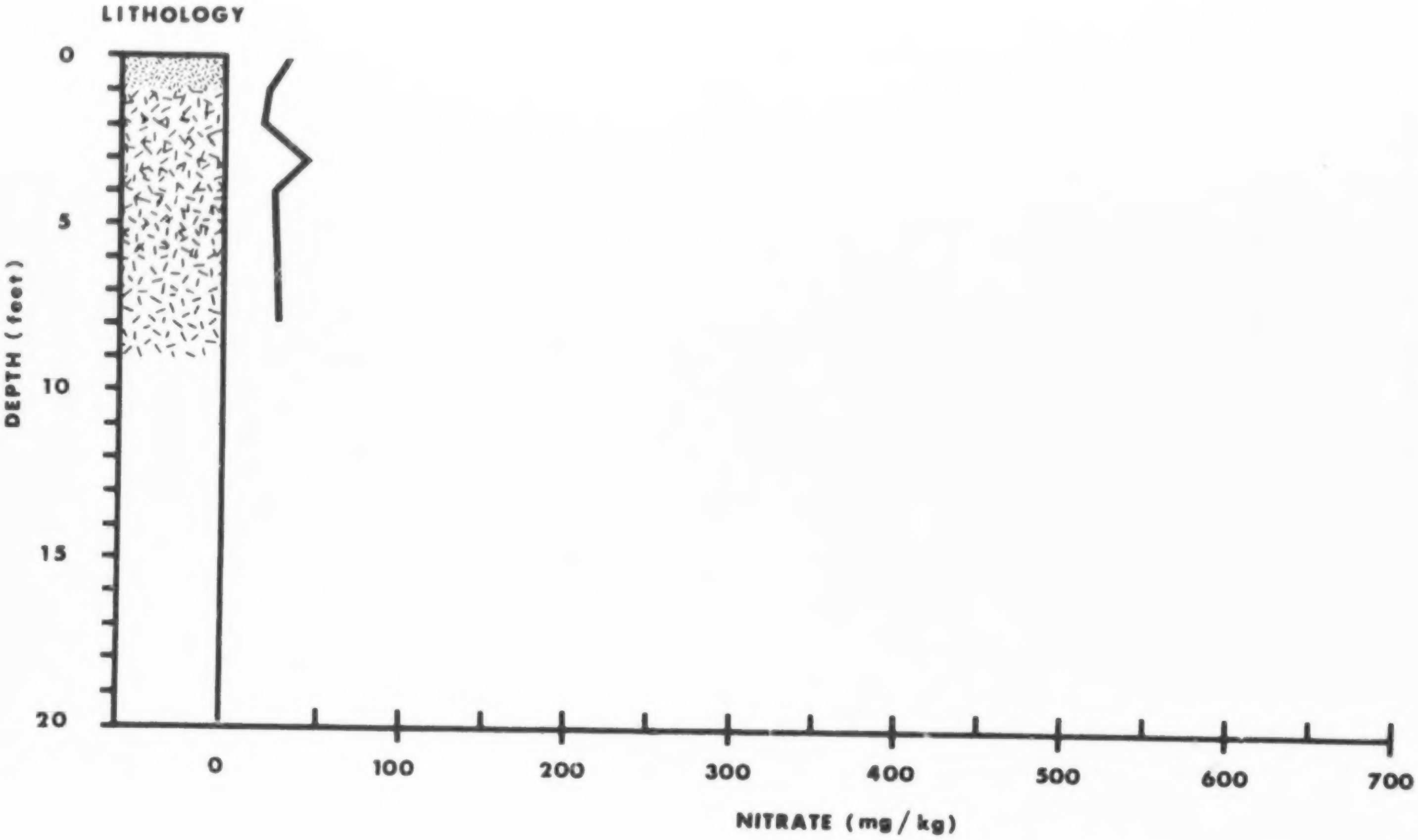
Hole 49. Located in a sorghum field 900 feet north of hole 48. No history of cattle or fertilizer. 275 #/acre-foot.



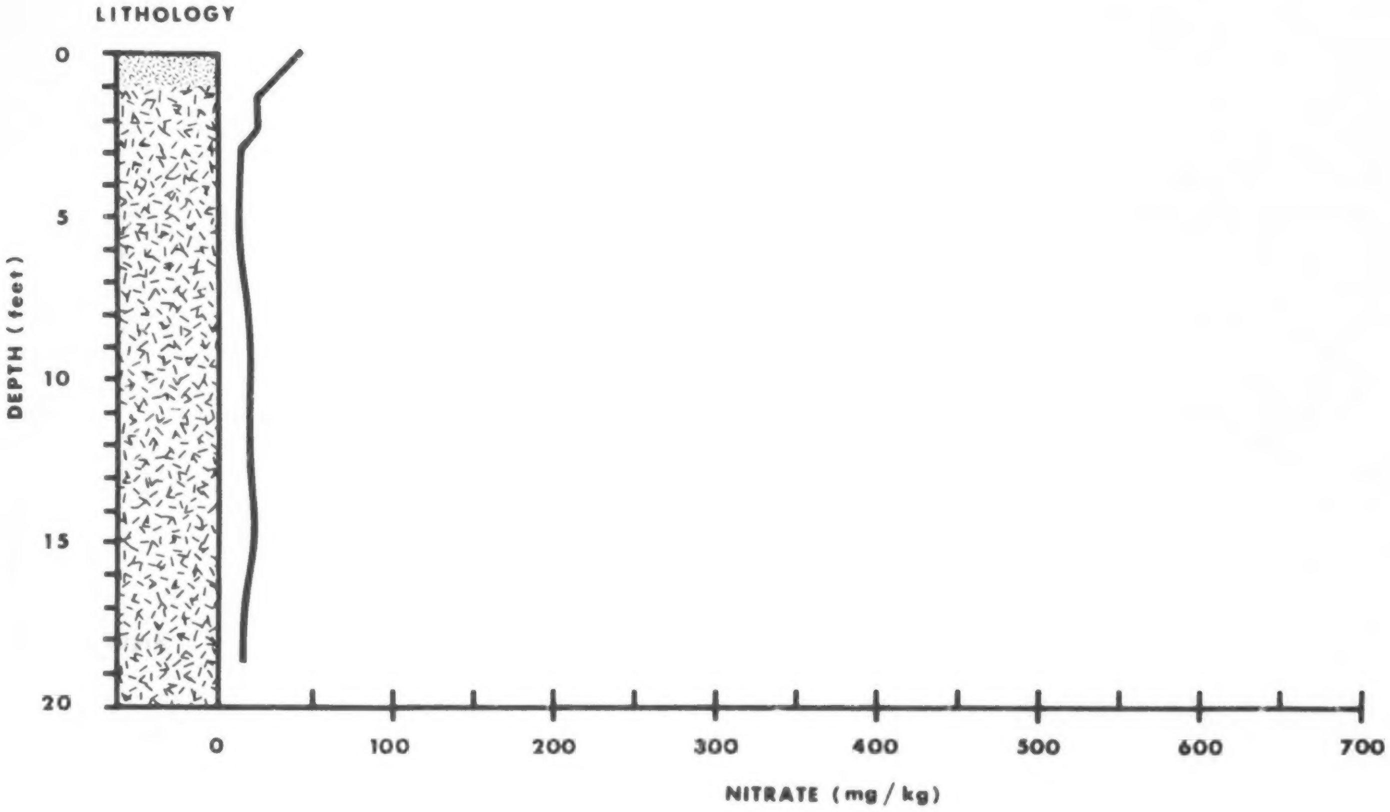
Hole 50. Located in a mesquite pasture 1/3 mile northwest of hole 49. Nitrate is fairly low. 125 #/acre-foot.



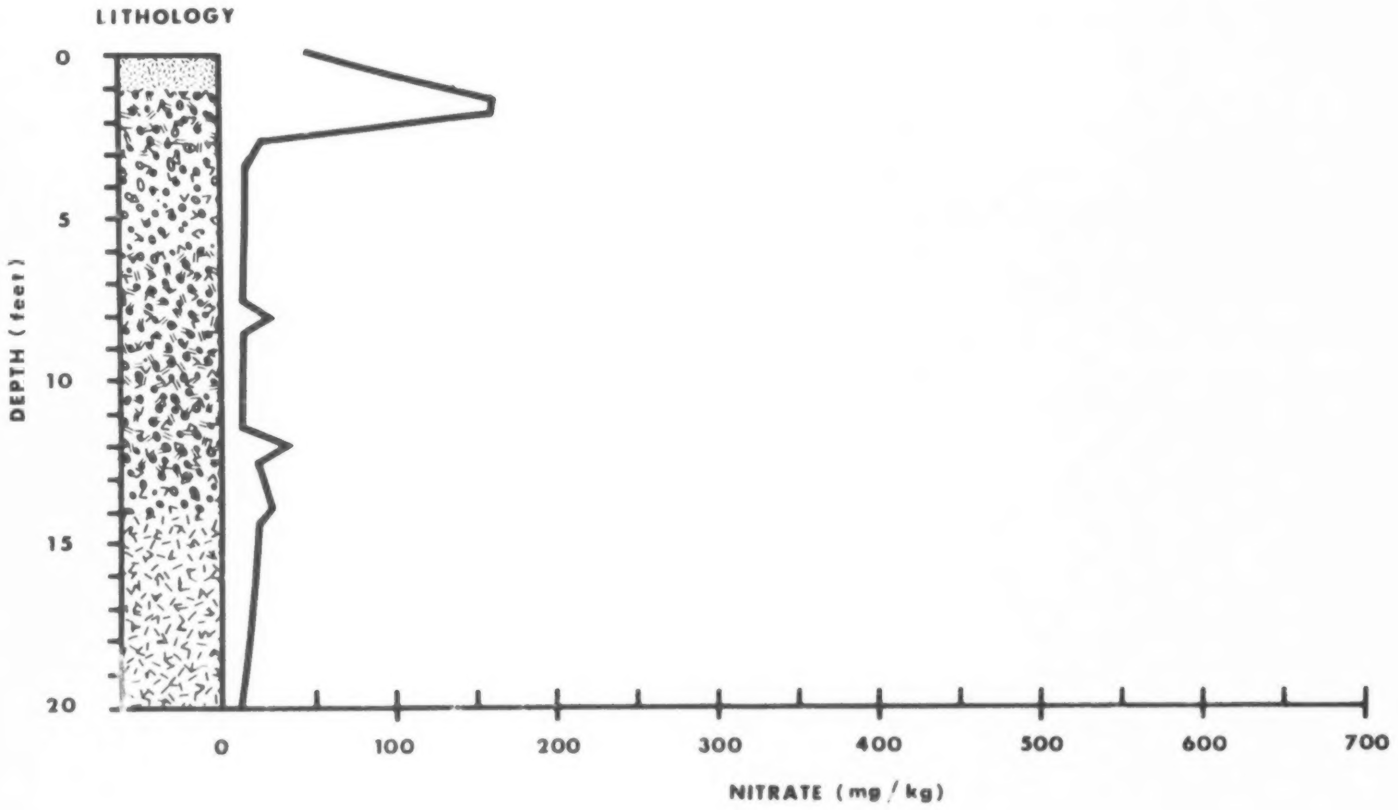
Hole 51. Located in a mesquite pasture 600 feet north of hole 50.
340 #/acre-foot.



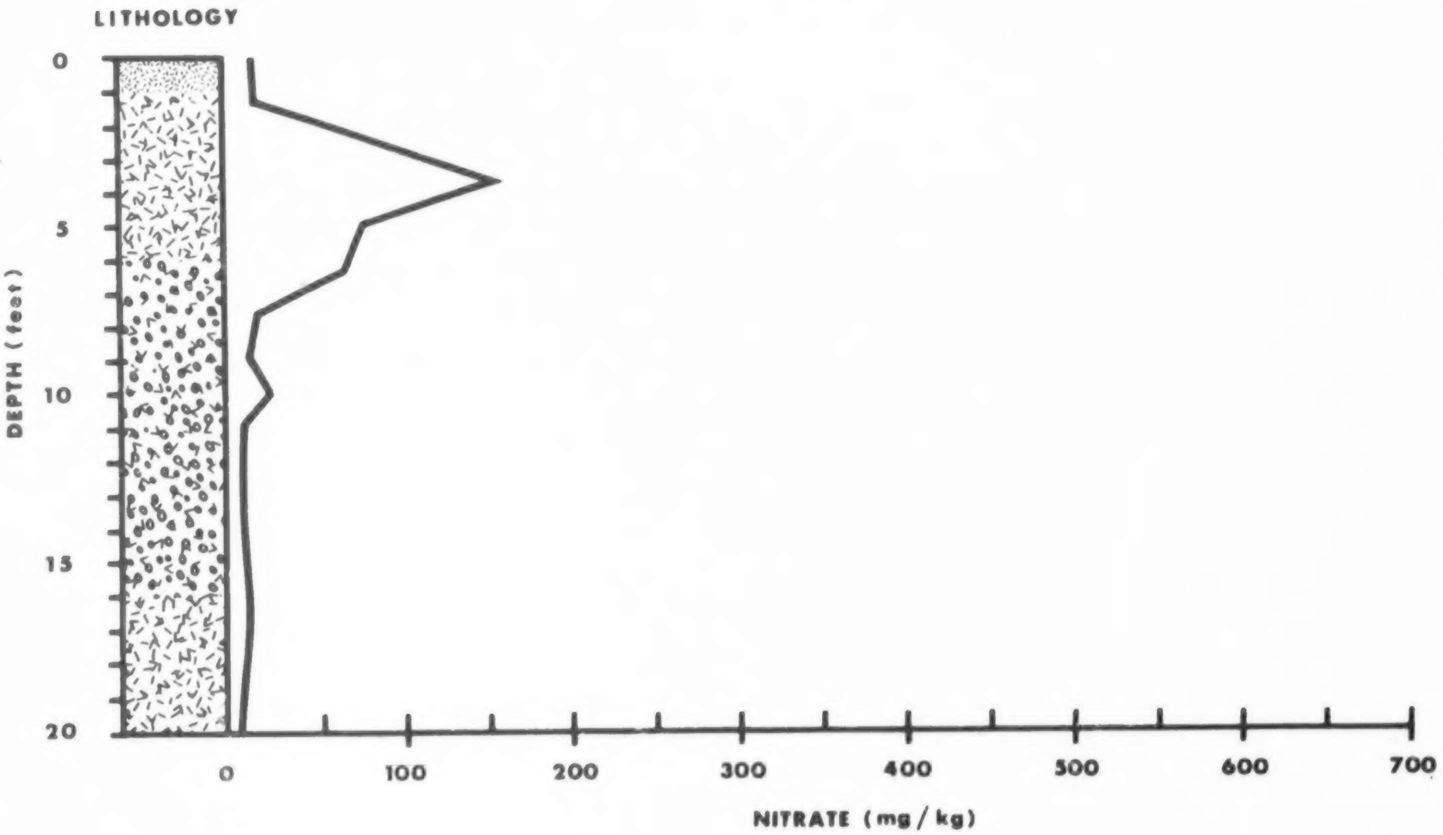
Hole 52. Located 1/3 mile southeast of well 67 (288 ppm nitrate, 8 feet to water) and near a seep area. Very shallow water table. 178 #/acre-foot.



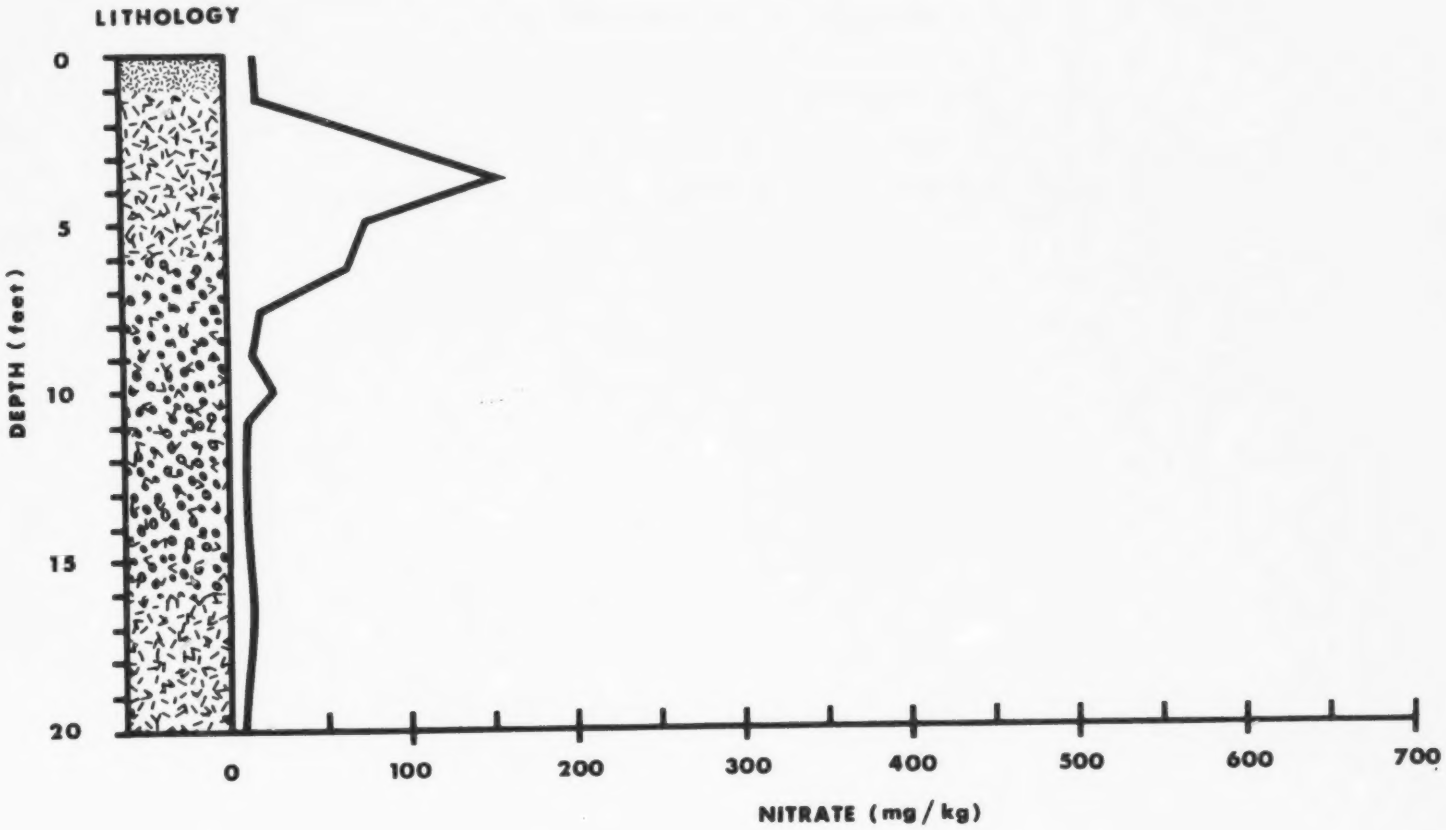
Hole 53. Located 1/5 mile east of well 67 (288 ppm nitrate. 8 feet to water) in a cotton field. 130 #/acre-foot.



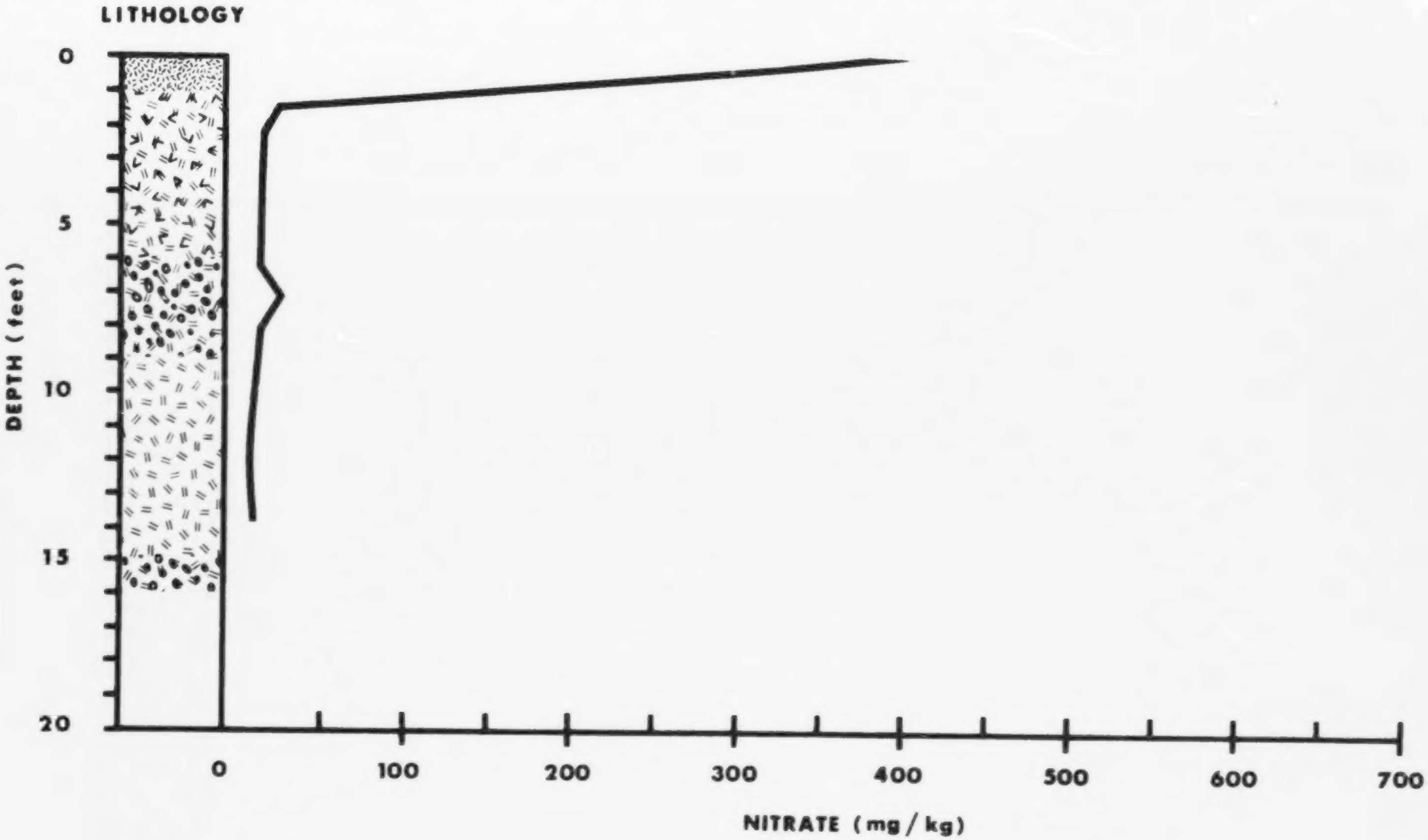
Hole 54. Located 1/4 mile south of well 67 (288 ppm nitrate, 8 feet to water) in a pasture where cattle graze. 215 #/ acre-foot.



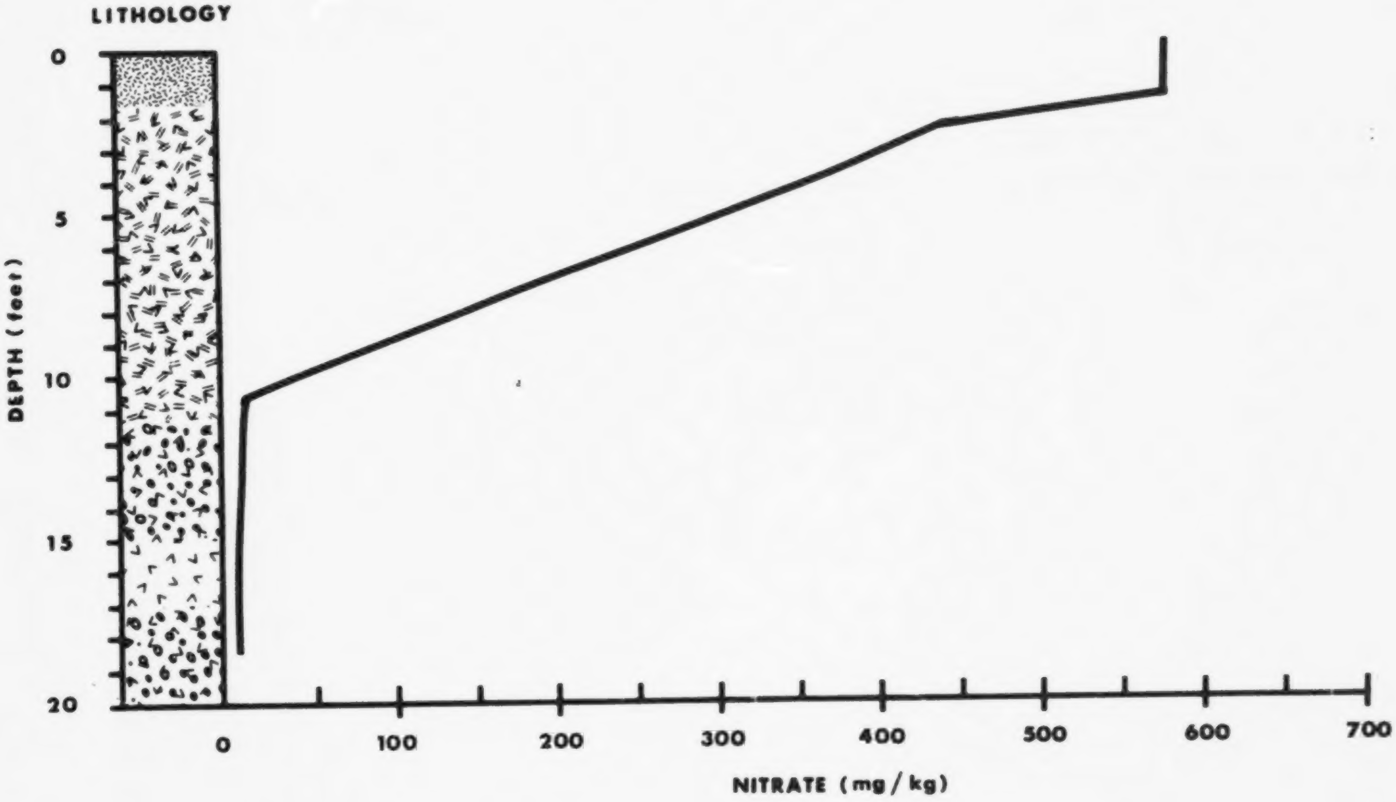
Hole 55. Located 1/4 mile southwest of well 67 (288 ppm nitrate, 8 feet to water) in a pasture where cattle graze. 220 #/acre-foot.



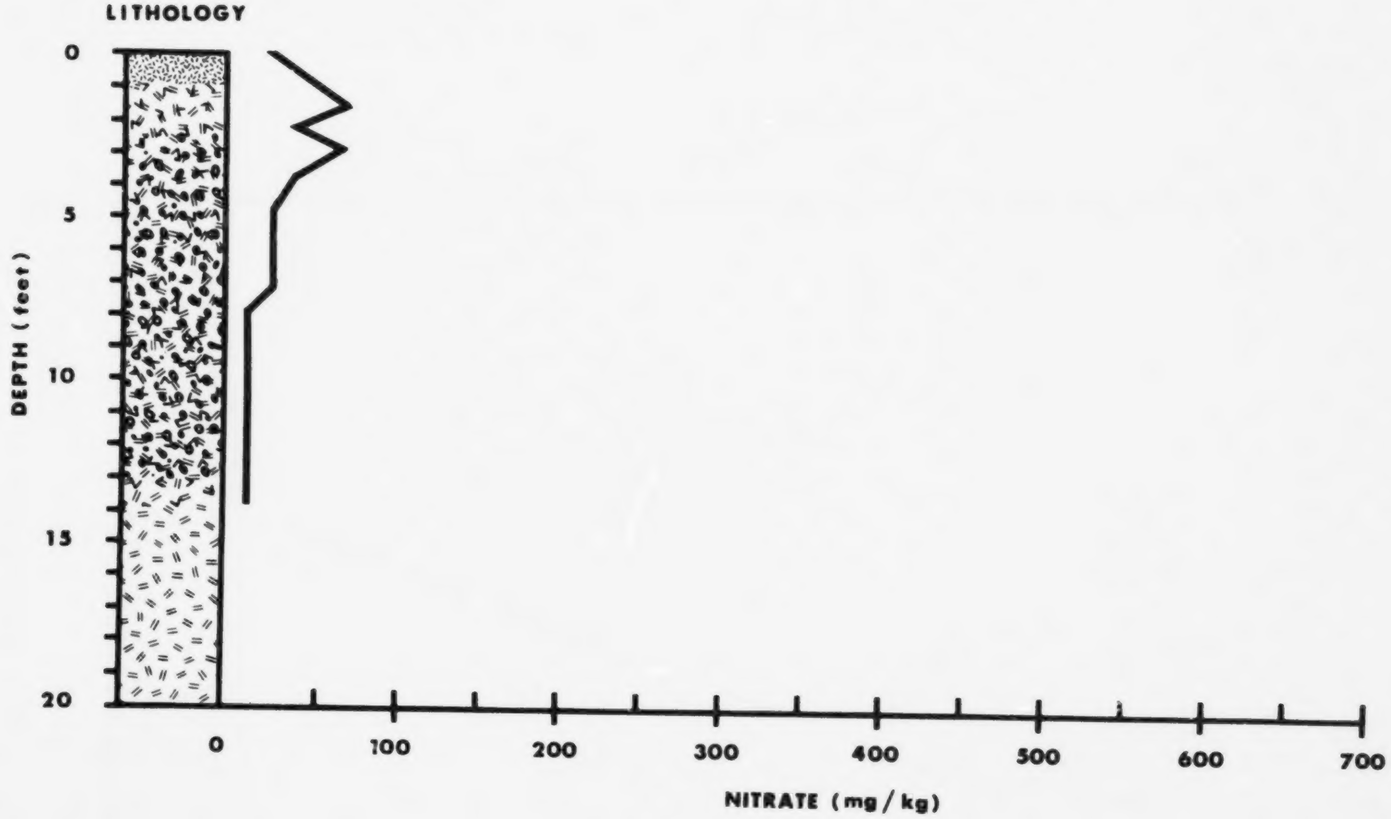
Hole 55. Located 1/4 mile southwest of well 67 (288 ppm nitrate, 8 feet to water) in a pasture where cattle graze. 220 #/acre-foot.



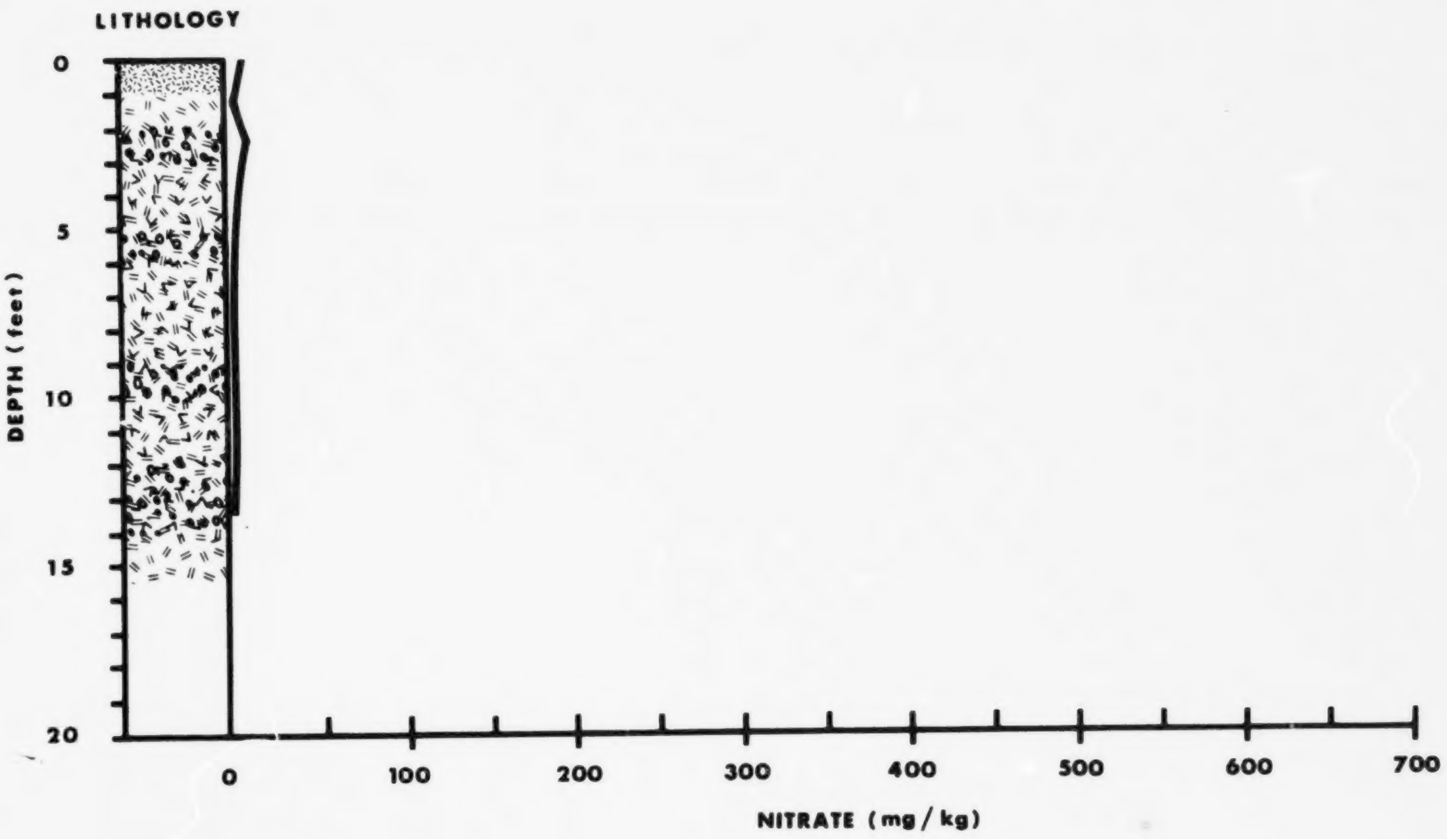
Hole 56. Located 400 feet west of hole 52 near a seep area.
263 #/acre-foot.



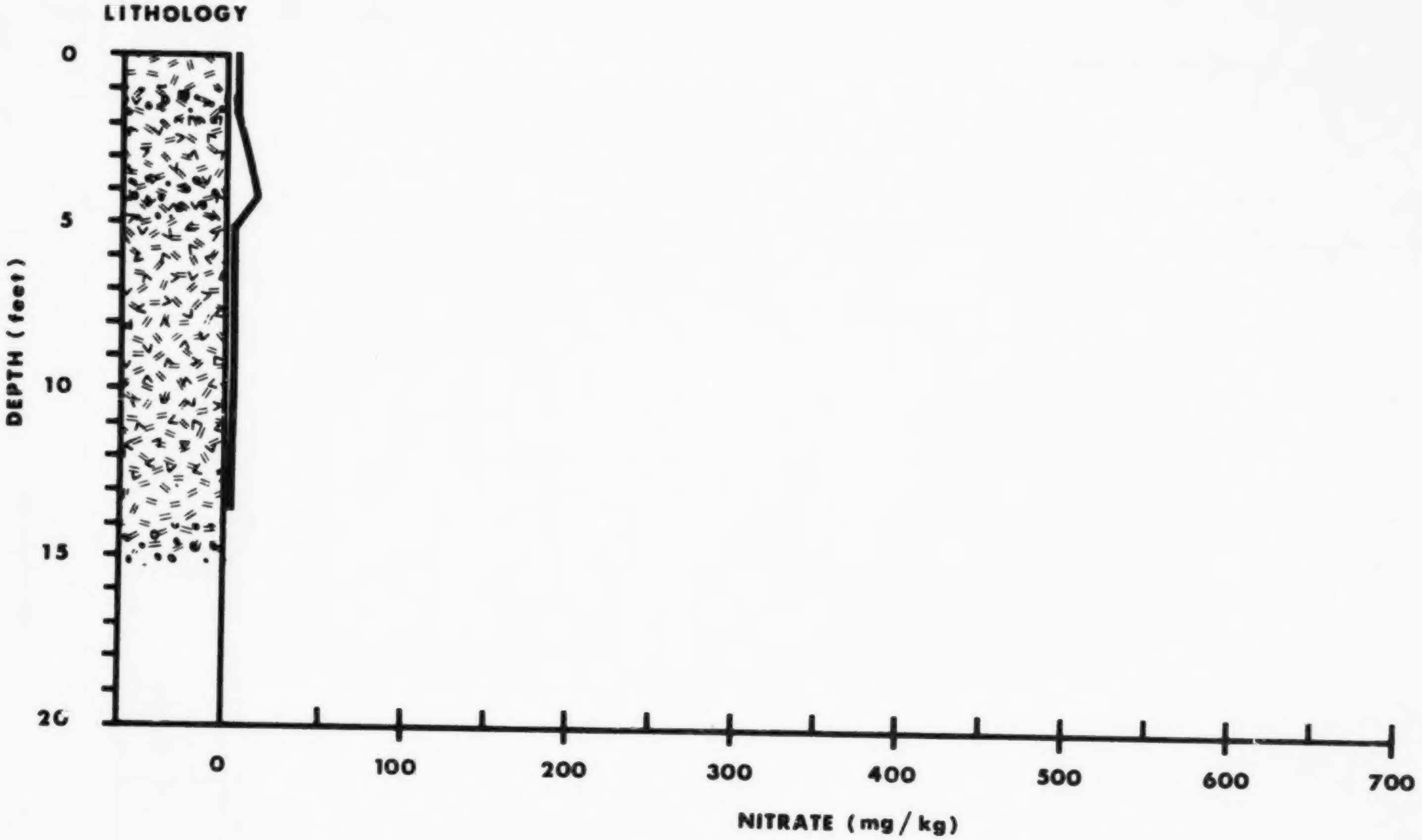
Hole 57. Located 100 feet east of well 67 (288 ppm nitrate, 8 feet to water) in barnyard which was abandoned three years ago.
945 #/acre-foot.



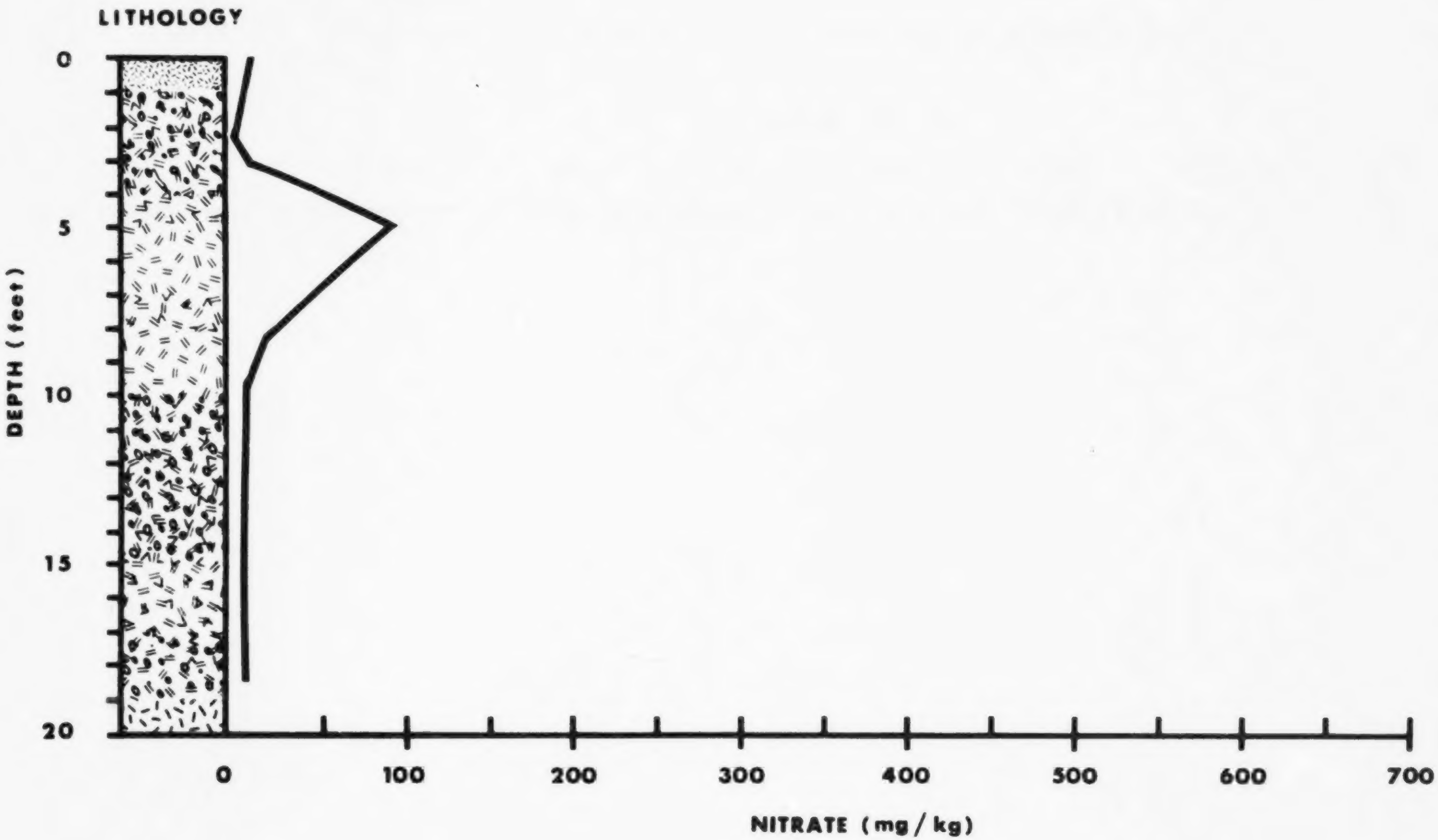
Hole 58. Located near well 67 (288 ppm nitrate, 8 feet to water). 160 #/acre-foot.



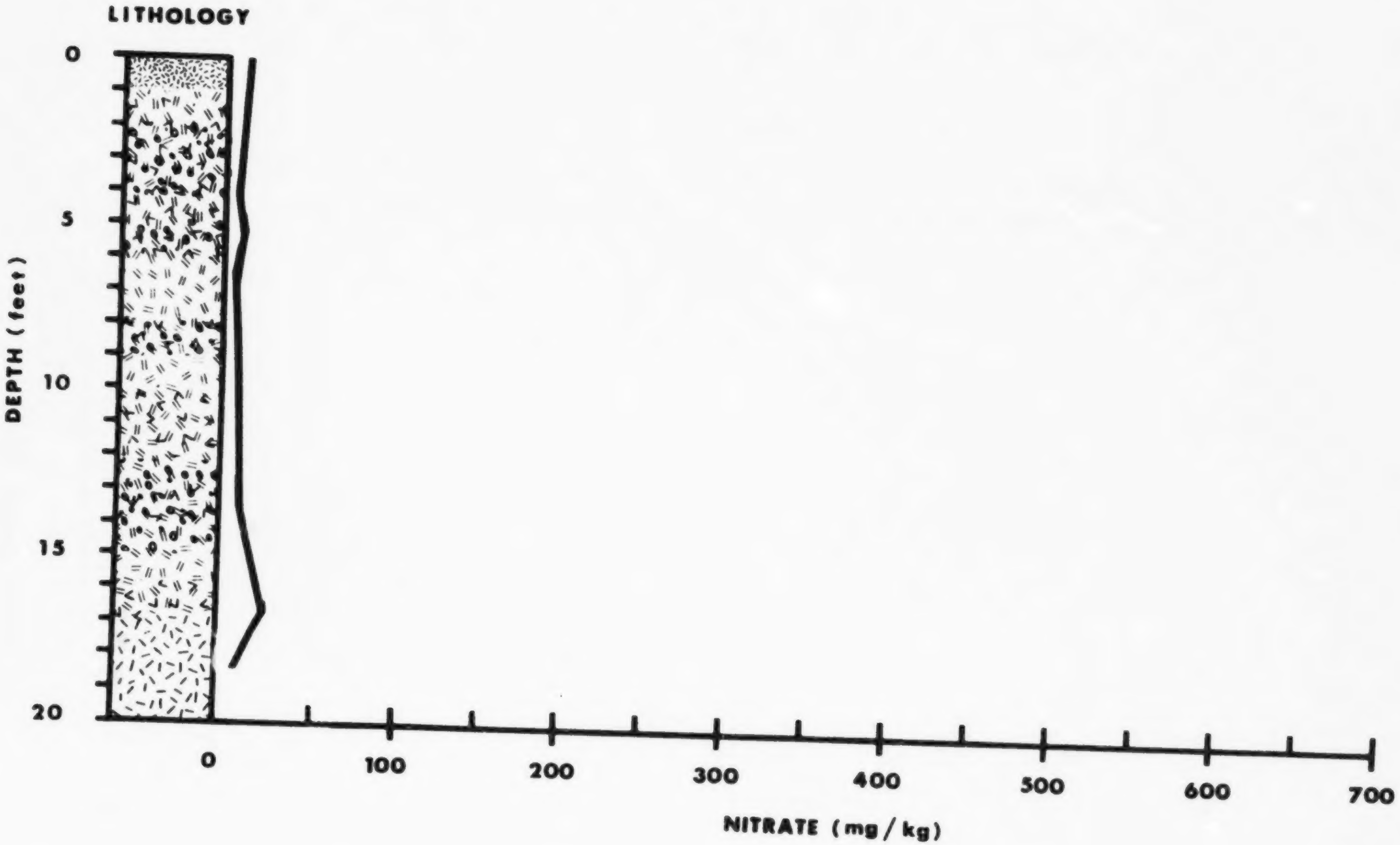
Hole 59. Located near well 67 (288 ppm nitrate, 8 feet to water) and hole 58. Very low nitrate. 50 #/acre-foot.



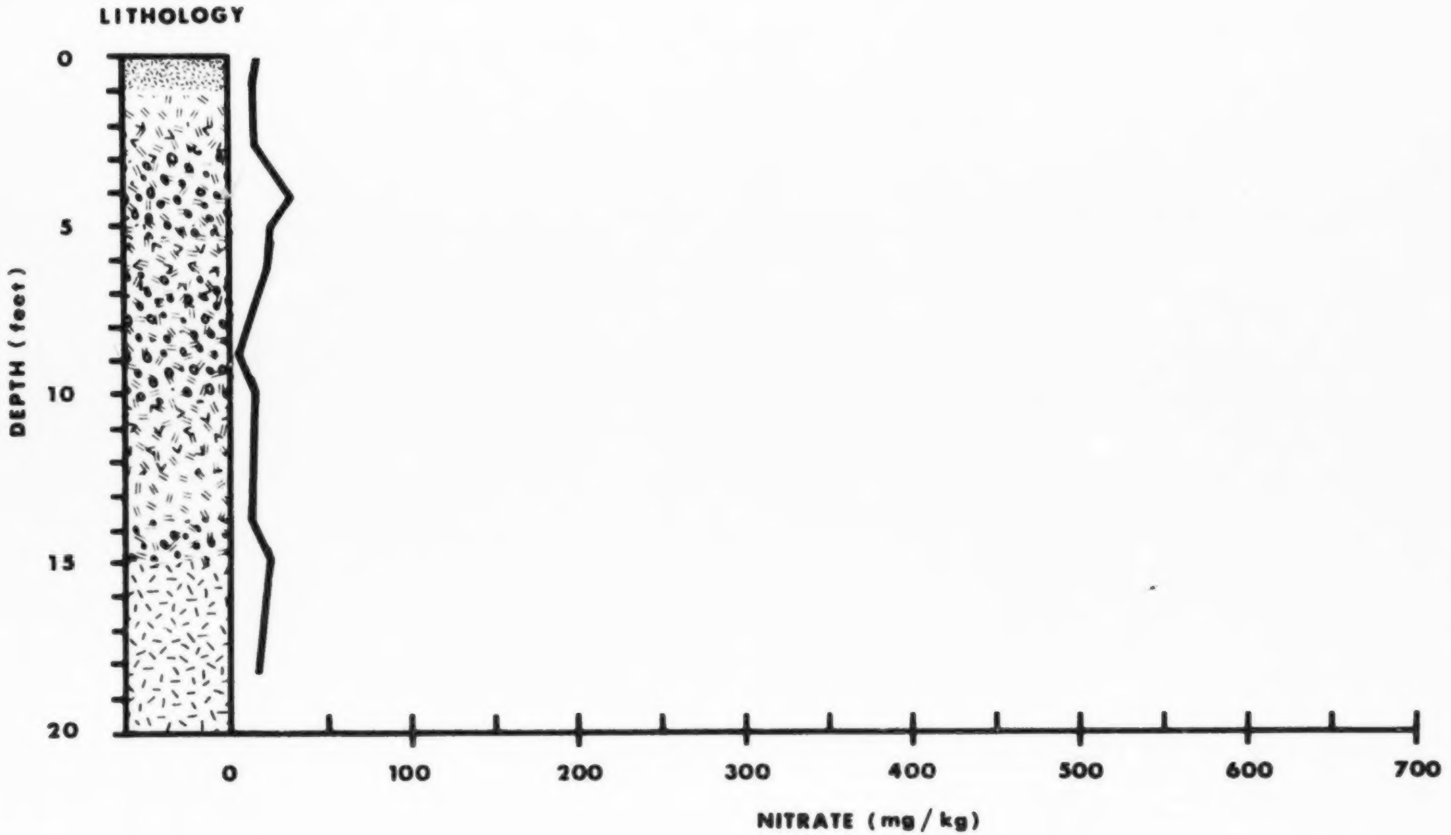
Hole 60. Located near hole 59. Lowest nitrate profile found.
40 #/acre-foot.



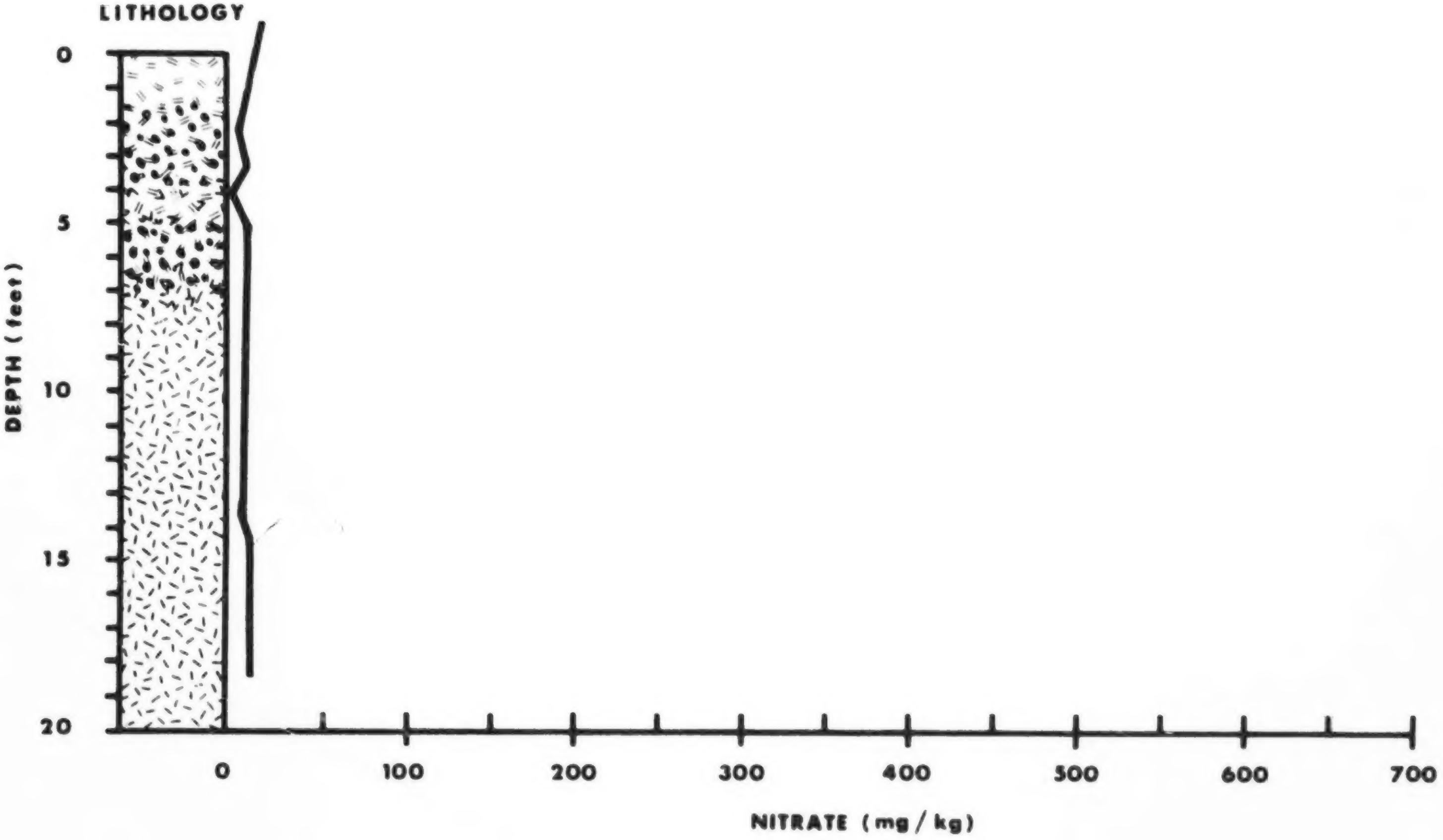
Hole 61. Located 1 mile east of well 338 (384 ppm nitrate, 16 feet to water) in a cultivated field. 172 #/acre-foot.



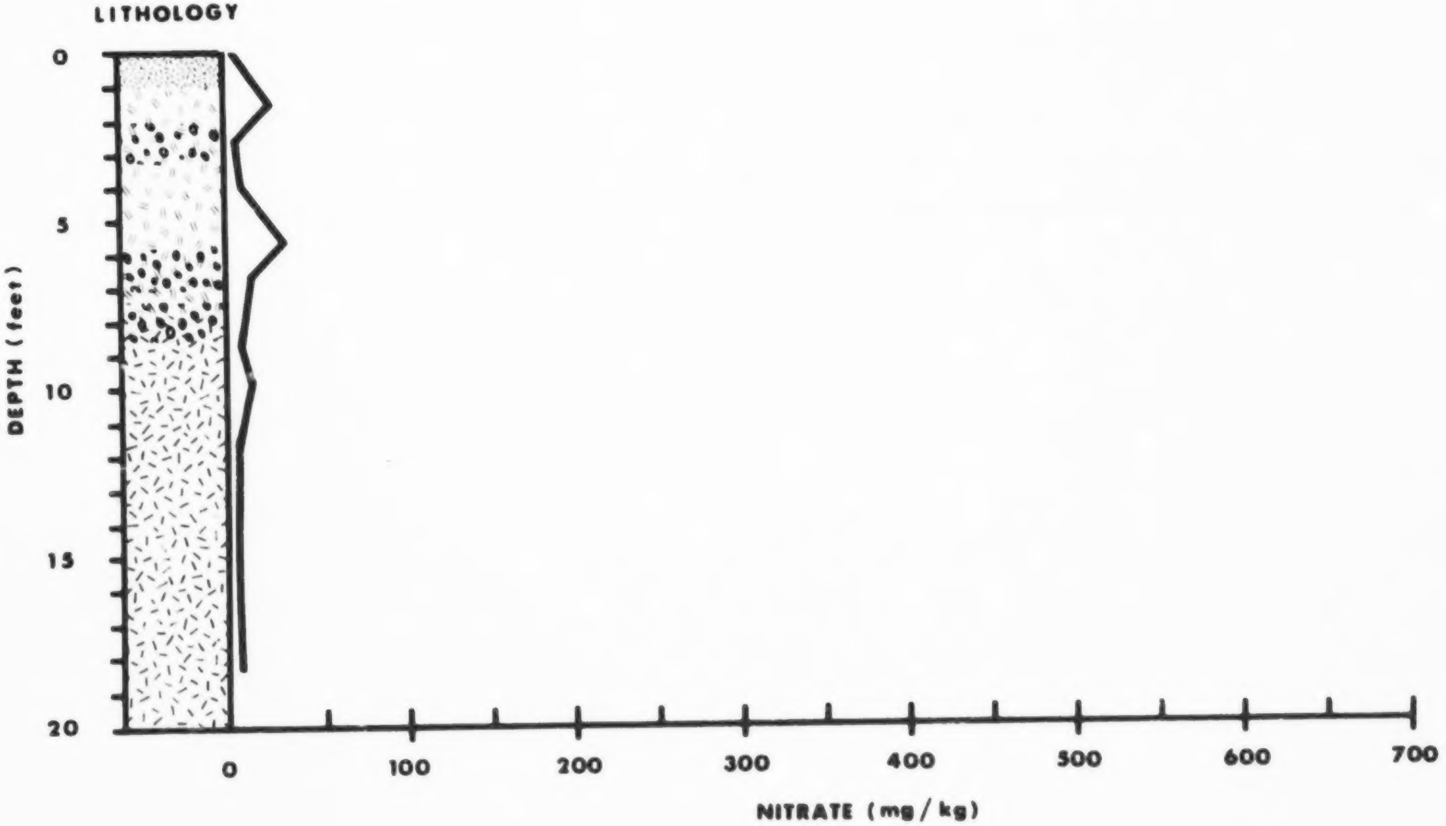
Hole 62. Located 1/8 mile southeast of hole 61 in a cultivated field. 67 #/acre-foot.



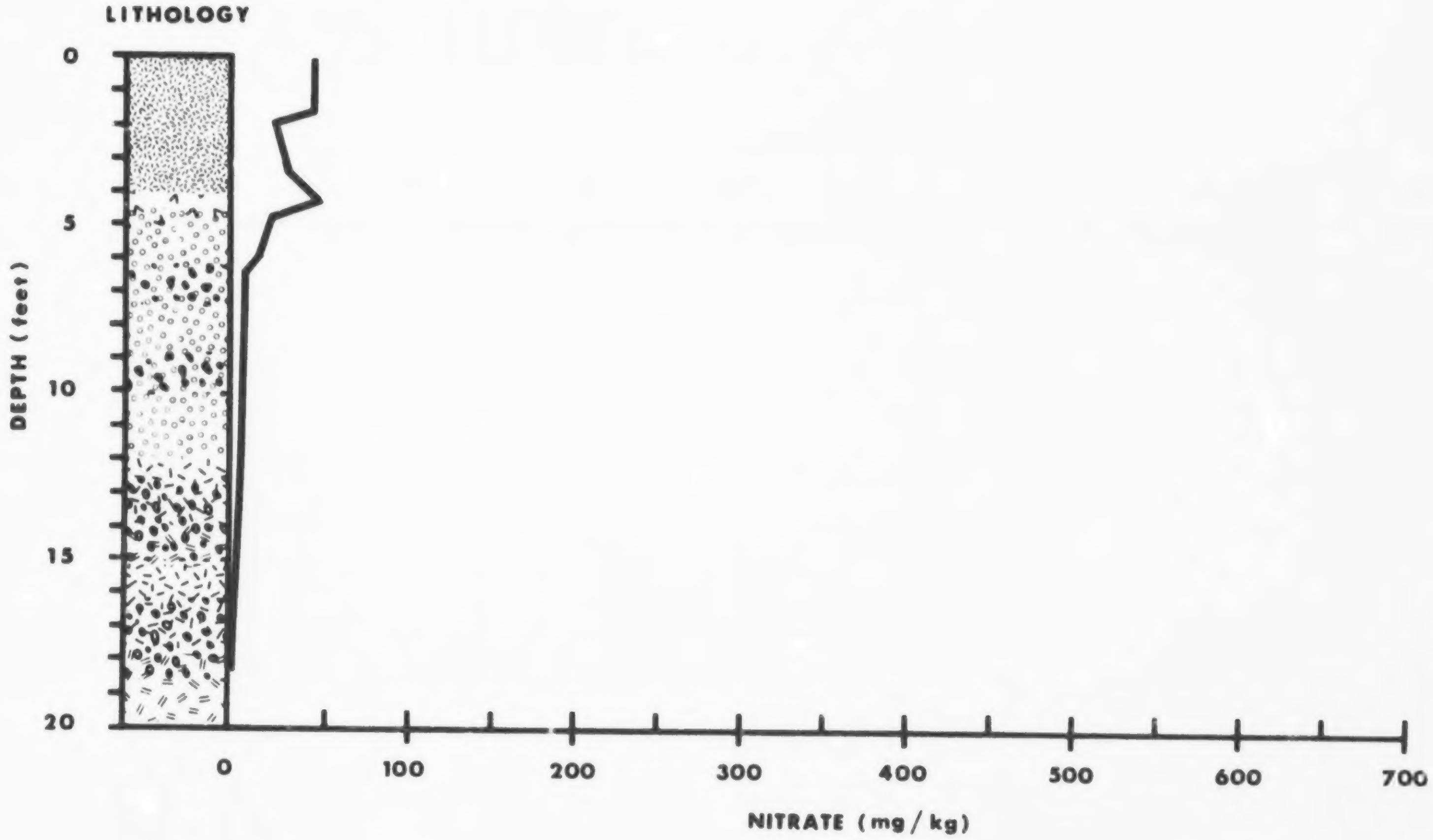
Hole 63. Located 1/8 mile east of hole 61 in a mesquite pasture. 92 #/acre-foot.



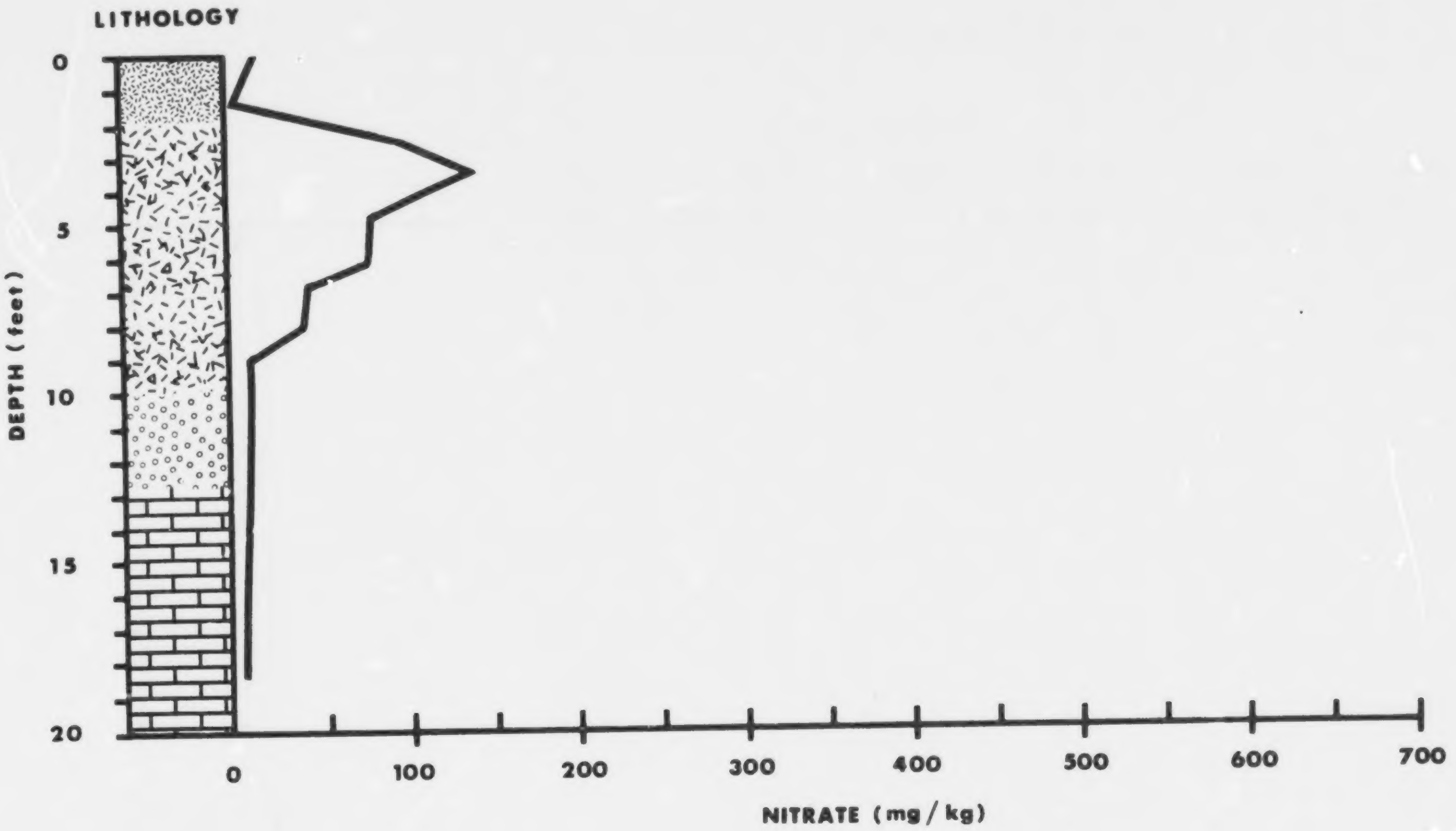
Hole 64. Located 1/8 mile east of hole 63 in a mesquite pasture.
62 #/acre-foot.



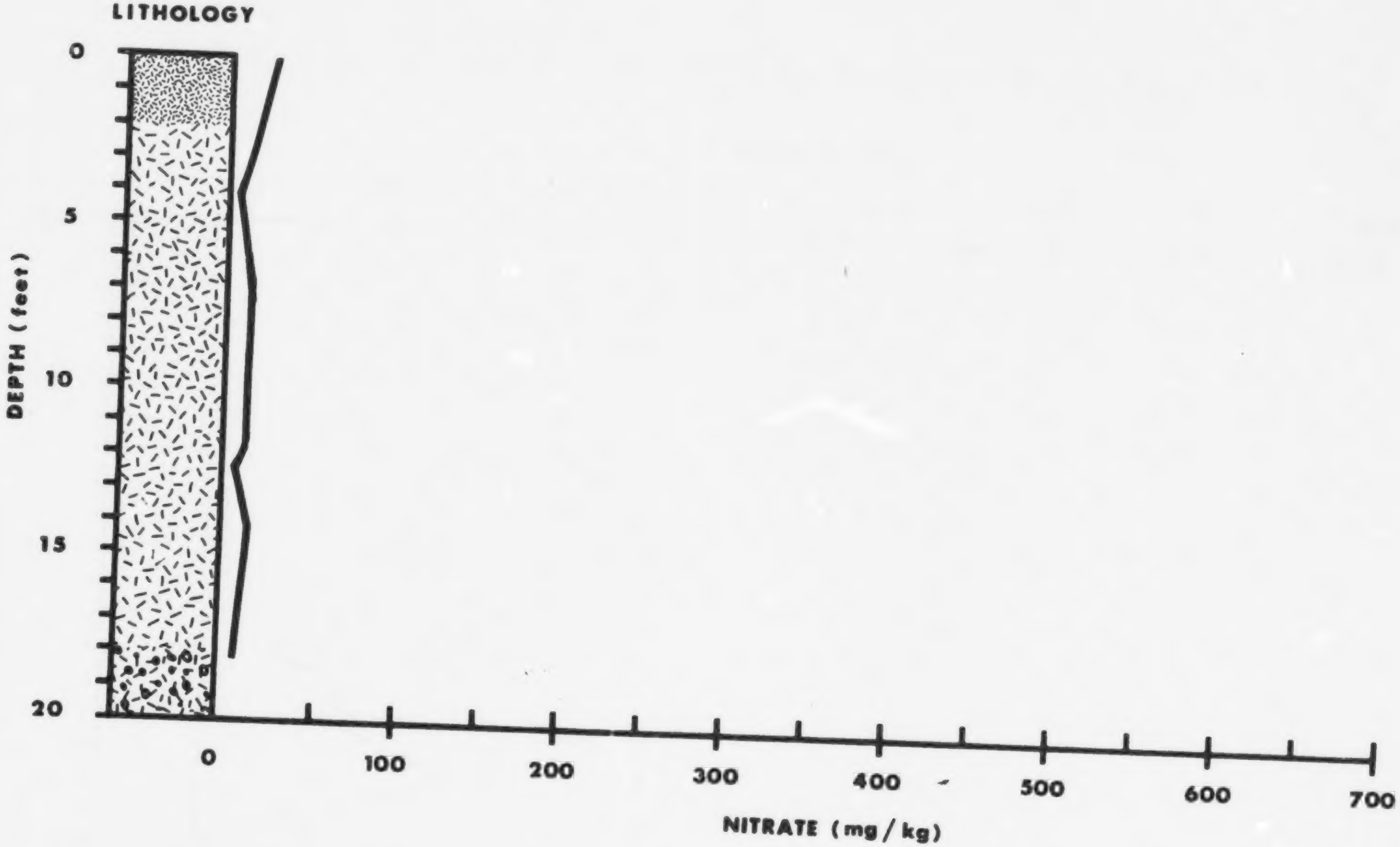
Hole 65. Located 1/2 mile south of well 338 (384 ppm nitrate, 16 feet to water) in a mesquite pasture. 85 #/acre-foot.



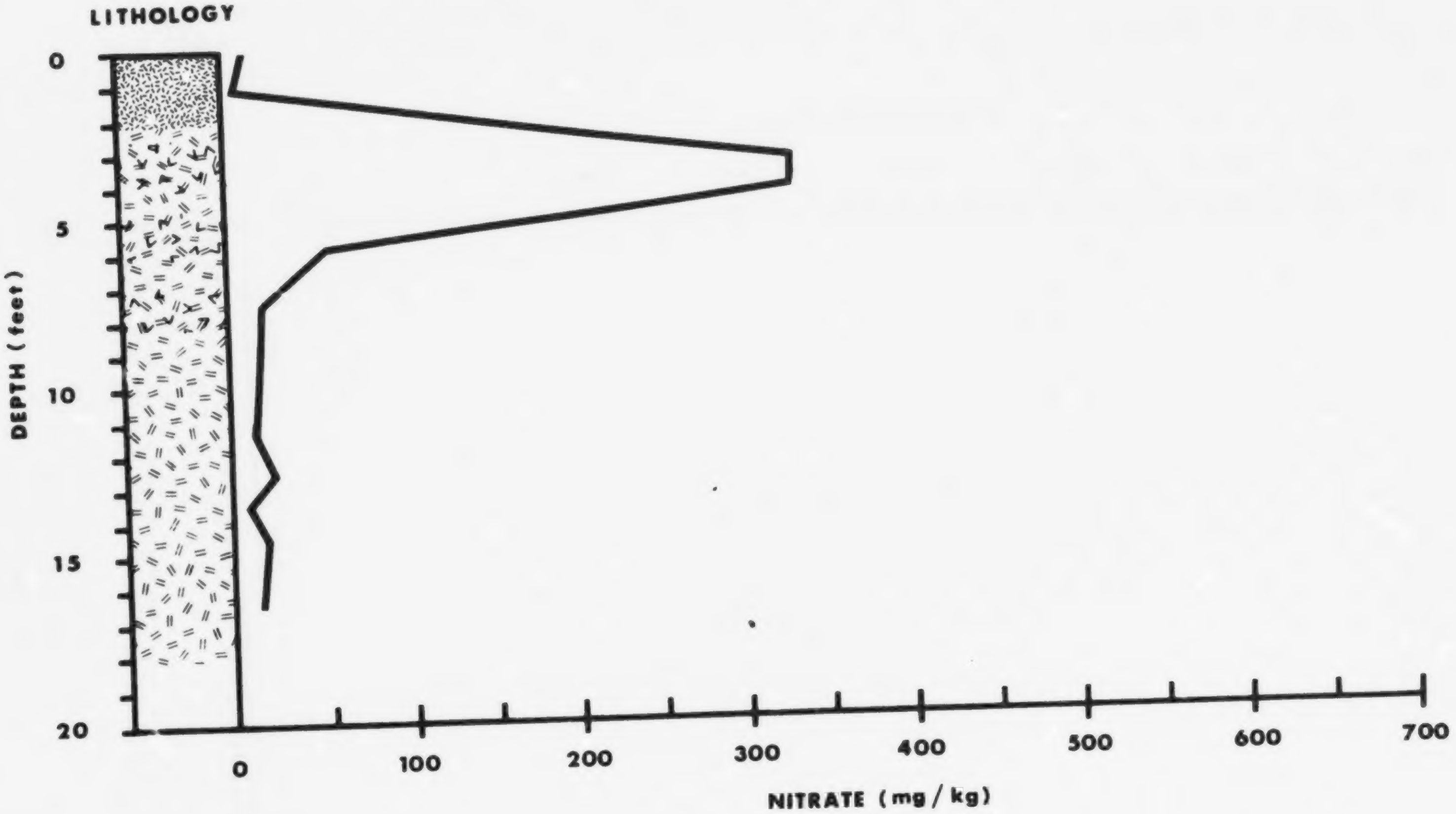
Hole 66. Located 1/8 mile east of hole 65 in a cultivated field.
110 #/acre-foot.



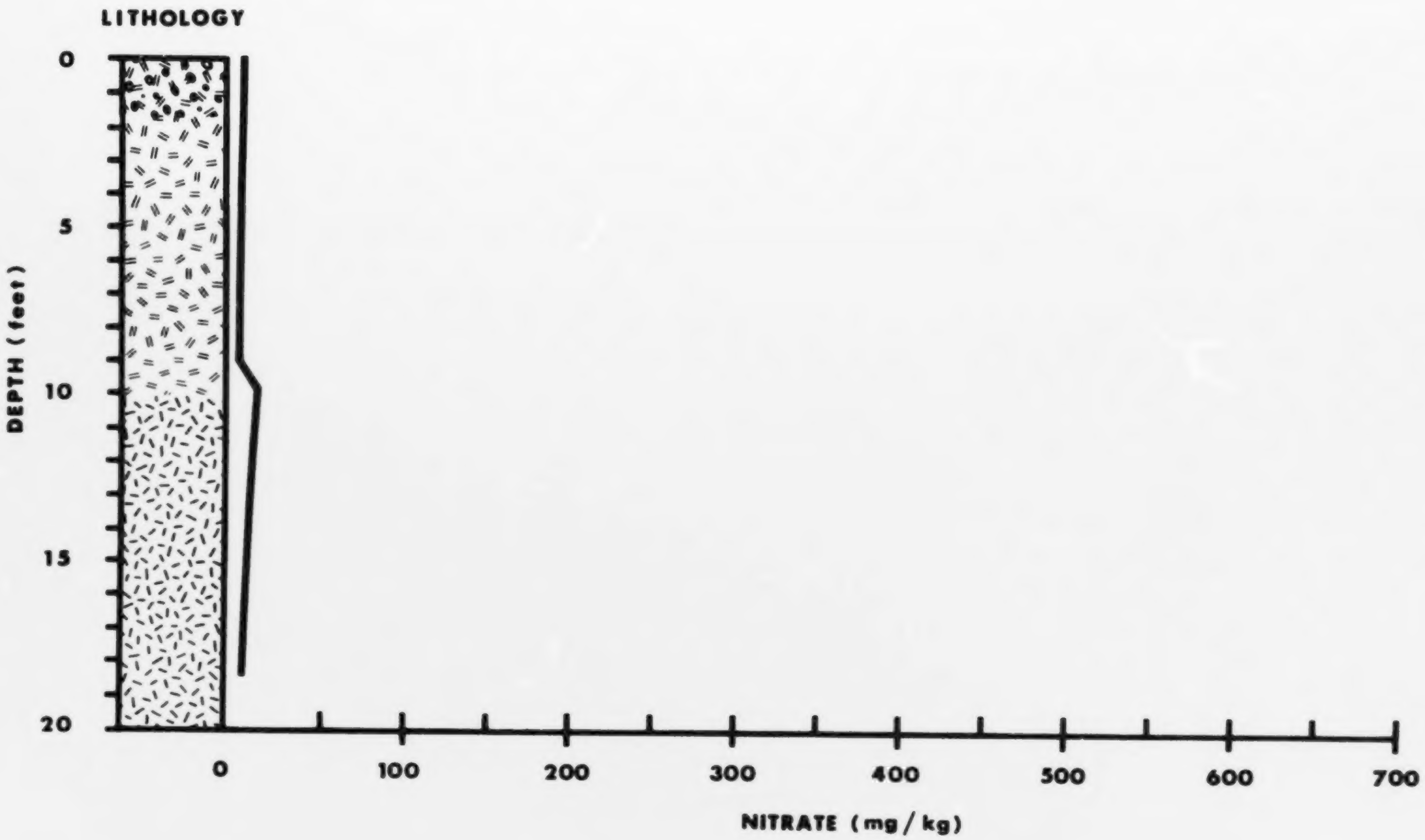
Hole 67. Located 200 feet northwest of farmhouse and 1/5 mile east of hole 66. 200 #/acre-foot.



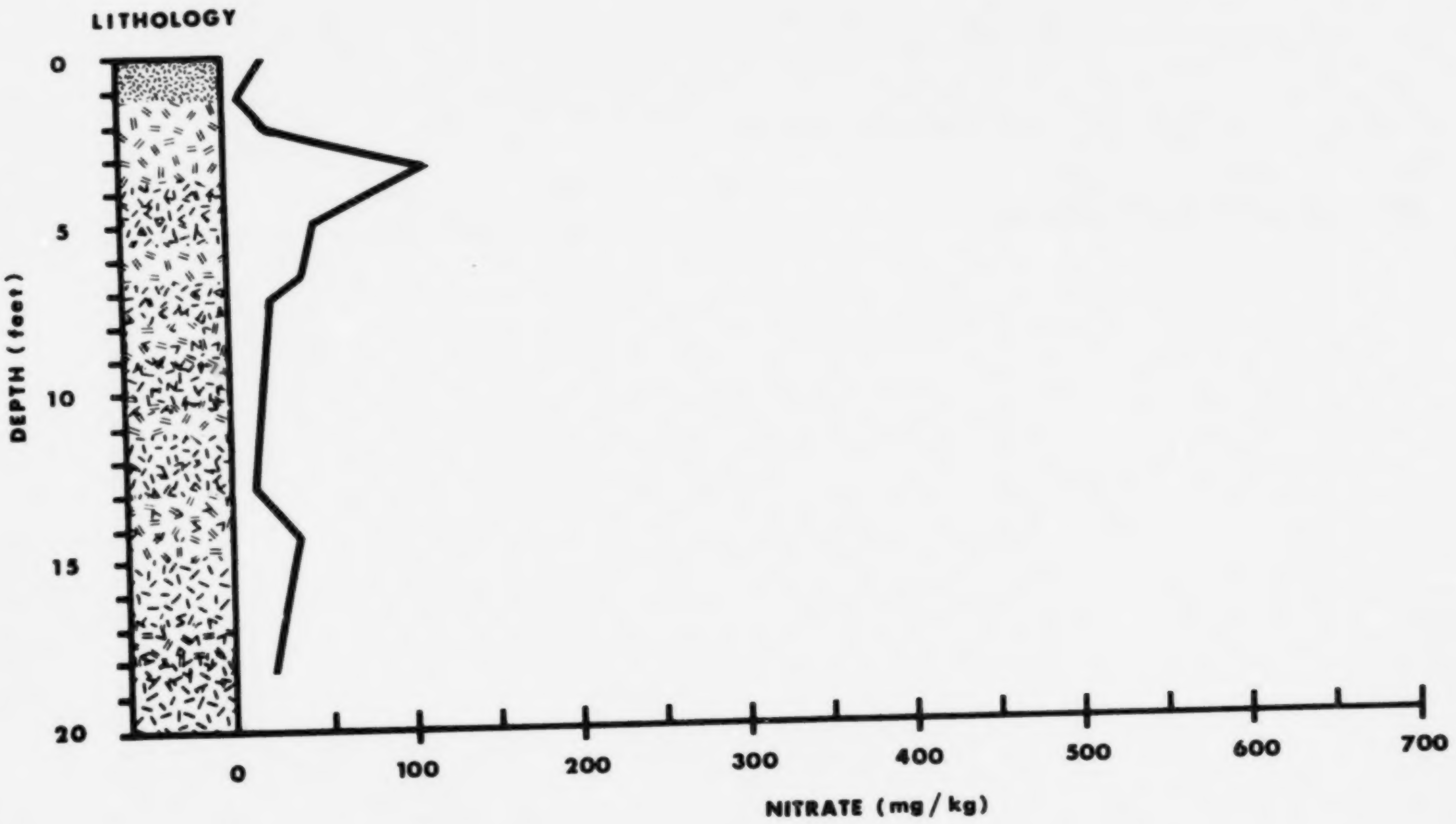
Hole 68. Located 100 feet east of well 408 (230 ppm nitrate, 12 feet to water) and near a drainage channel in clay. 77 #/acre-foot.



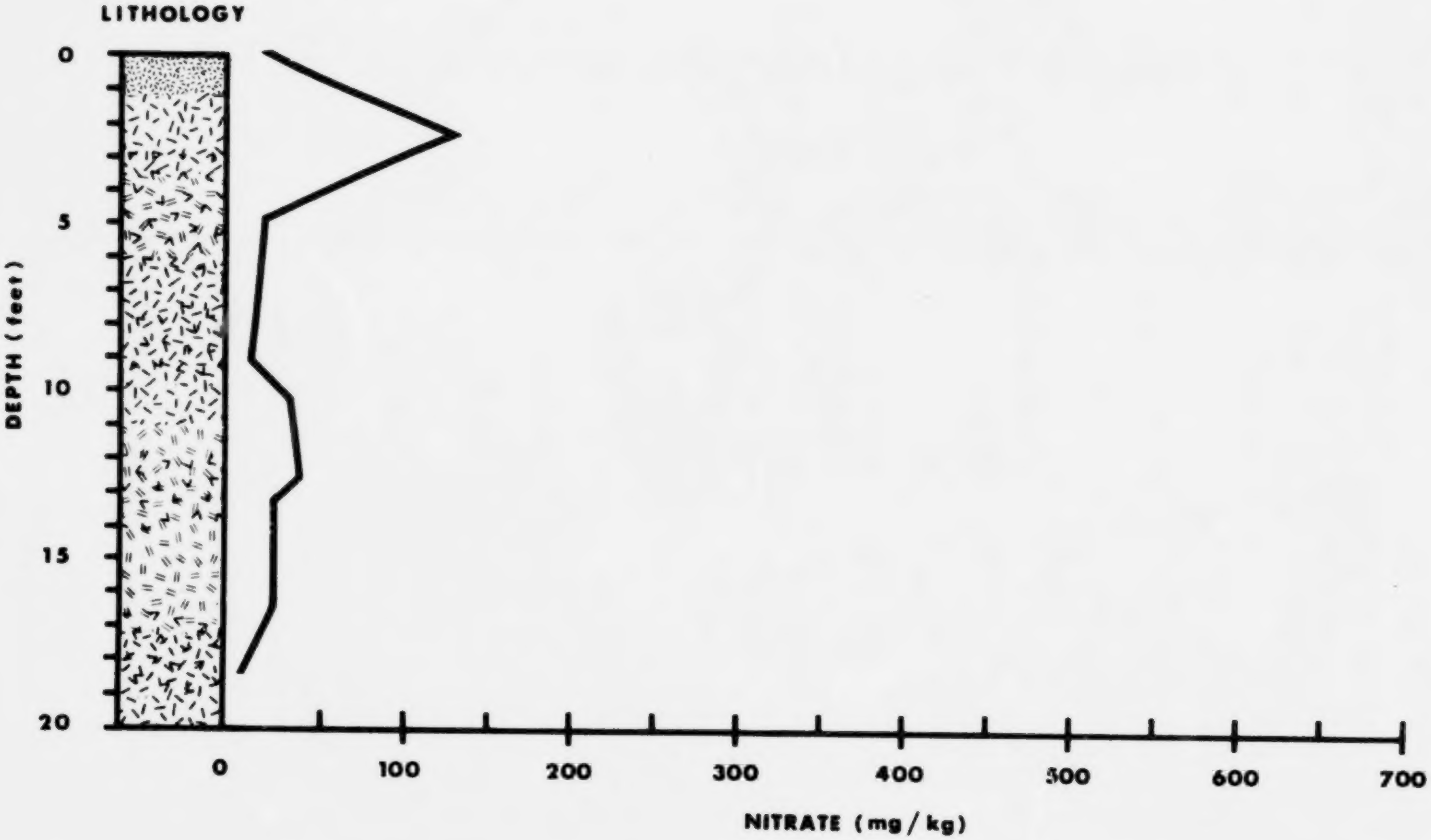
Hole 69. Located 100 feet northeast of farmhouse and 1/3 mile east of hole 68. 285 #/acre-foot.



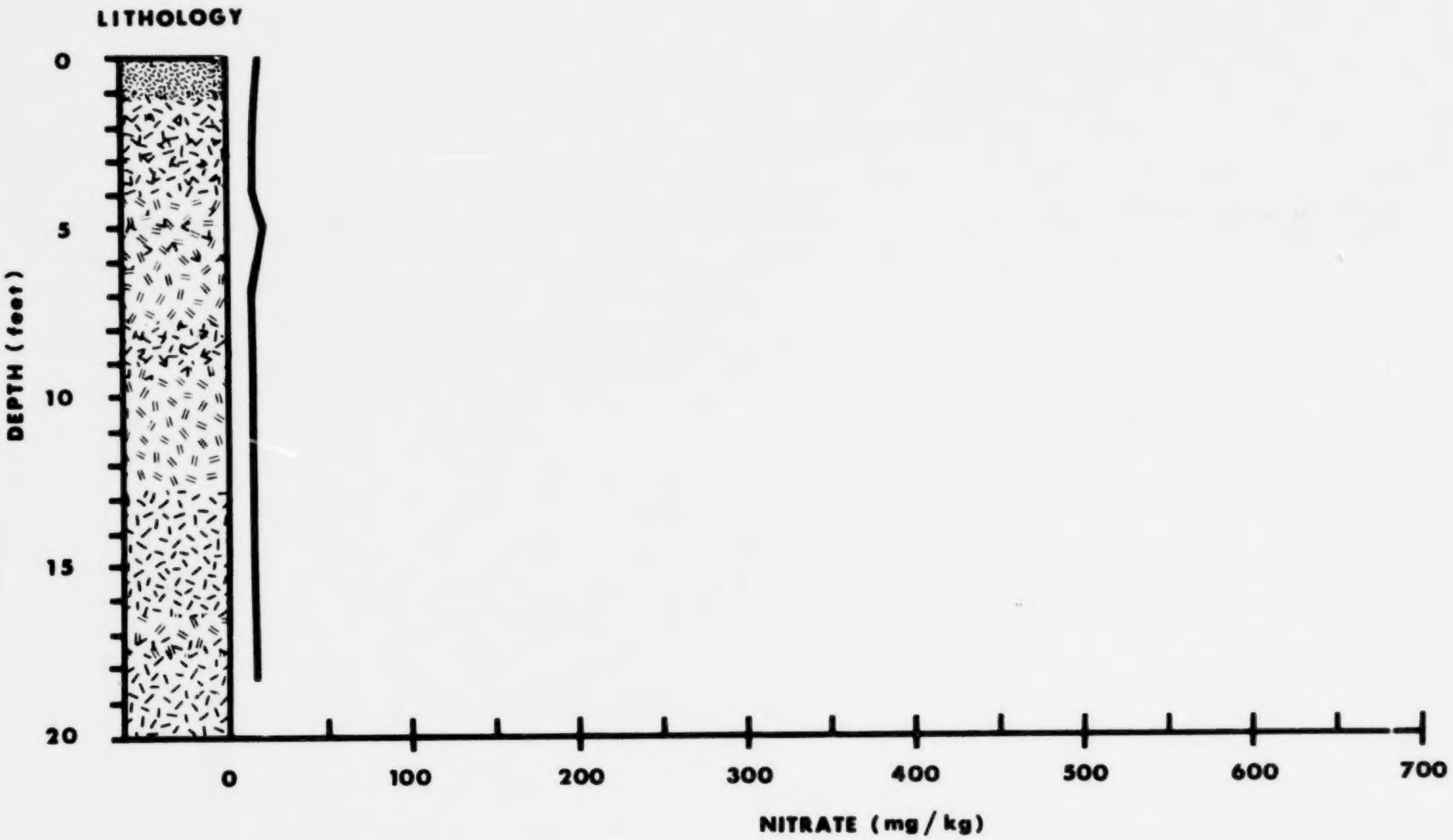
Hole 70. Located 1 mile northeast of well 523 (304 ppm nitrate, 3 feet to water) in a pasture. 65 #/acre-foot.



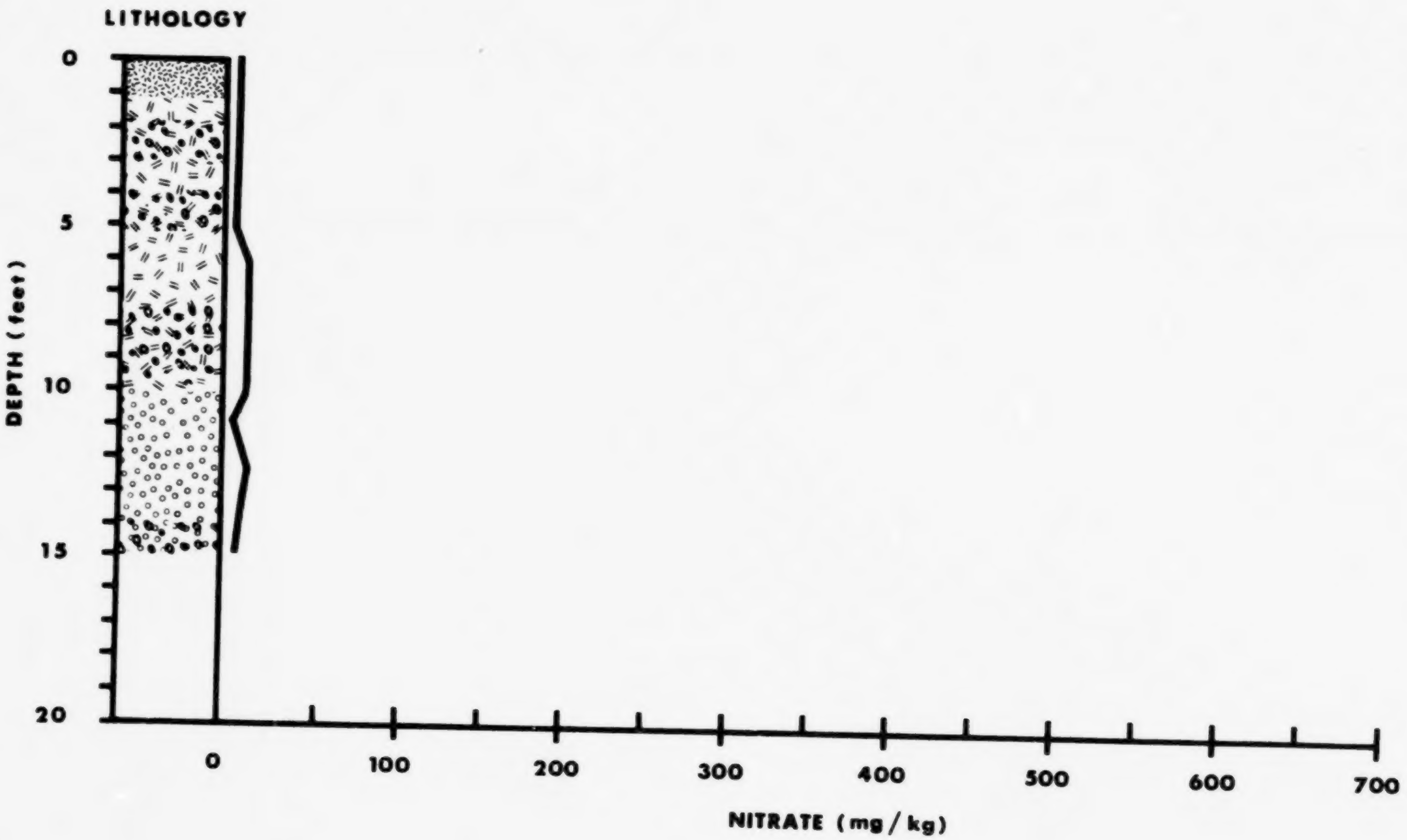
Hole 71. Located 1/2 mile south of hole 70 near a farmhouse.
212 #/acre-foot.



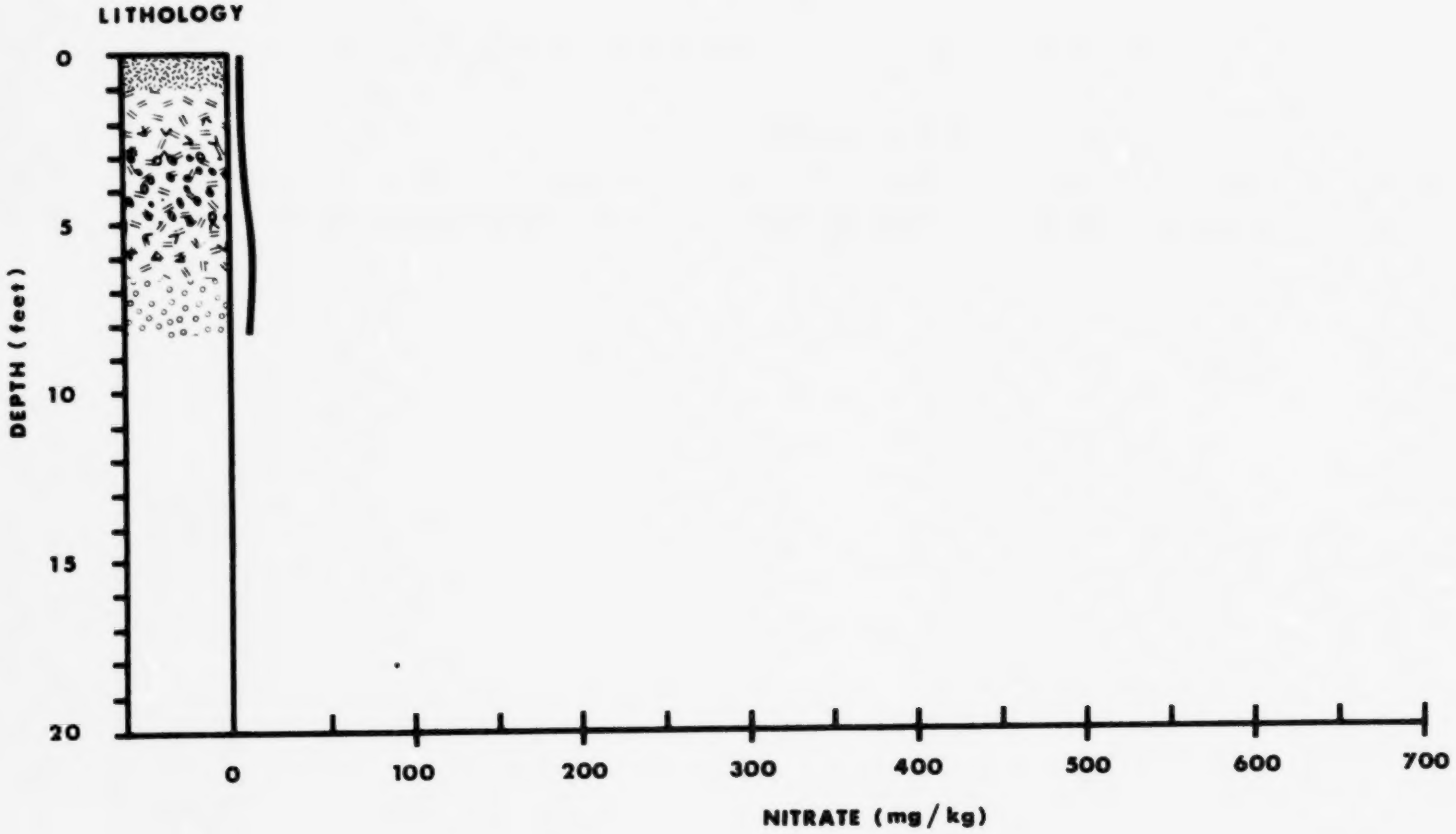
Hole 72. Located 2 miles east of well 773 (243 ppm nitrate, 4 feet to water) on a high point in a cultivated field. 245 #/acre-foot.



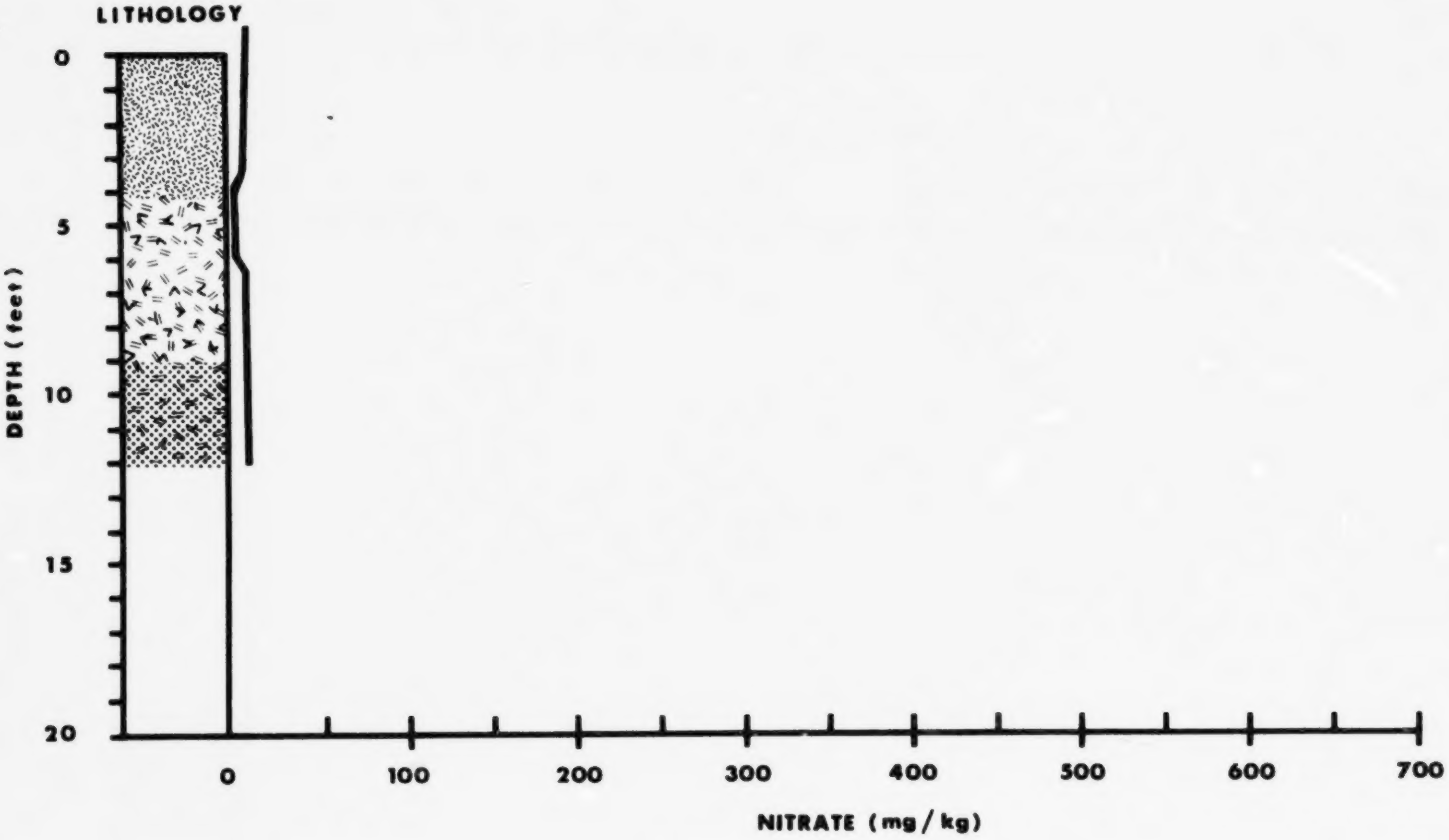
Hole 73. Located 1/5 mile south of hole 72 behind a terrace in cultivated field. 110 #/acre-foot.



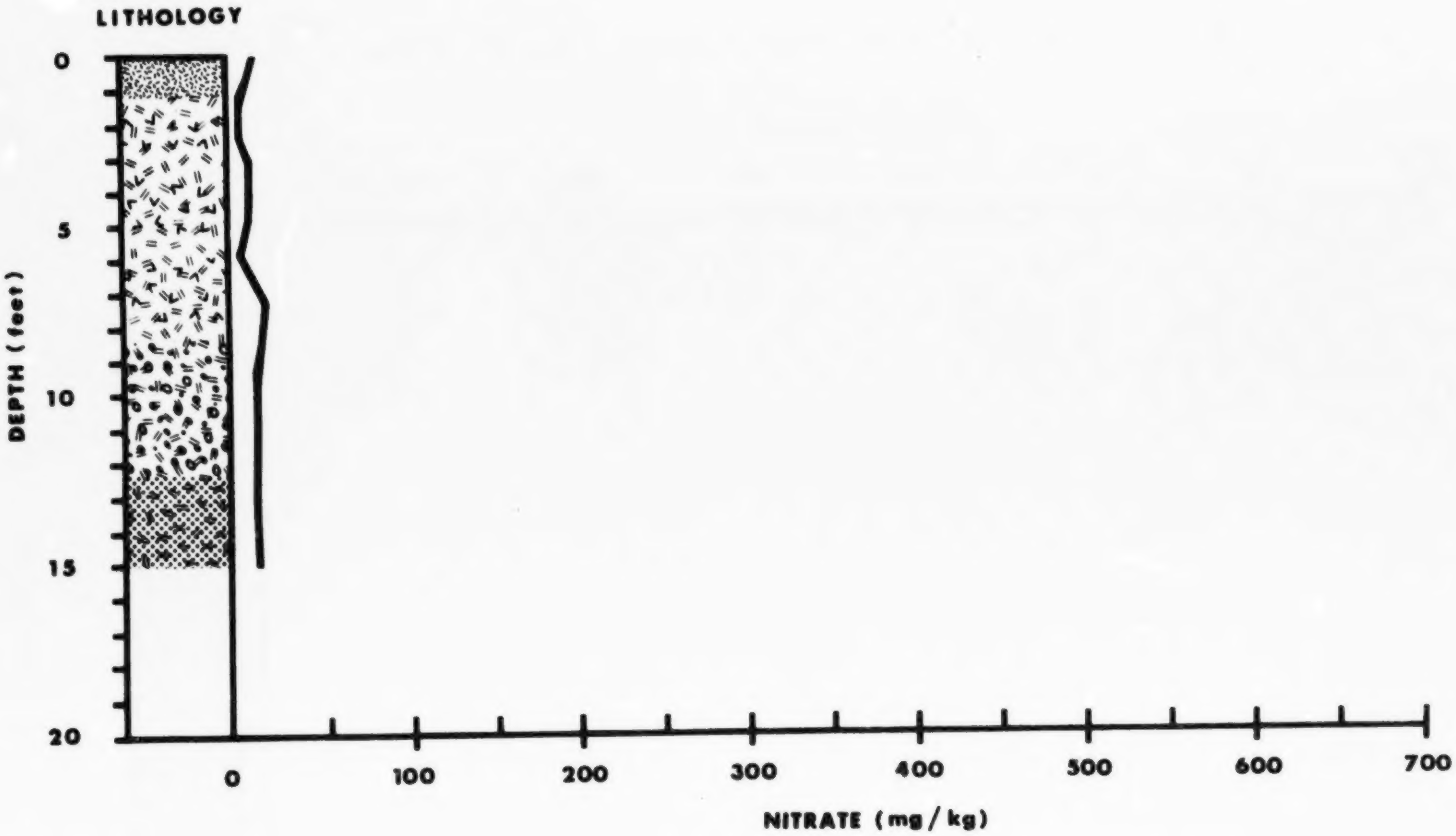
Hole 74. Located 1/8 mile northwest of well 301 (spring, 240 ppm nitrate) in a pasture. 73 #/acre-foot.



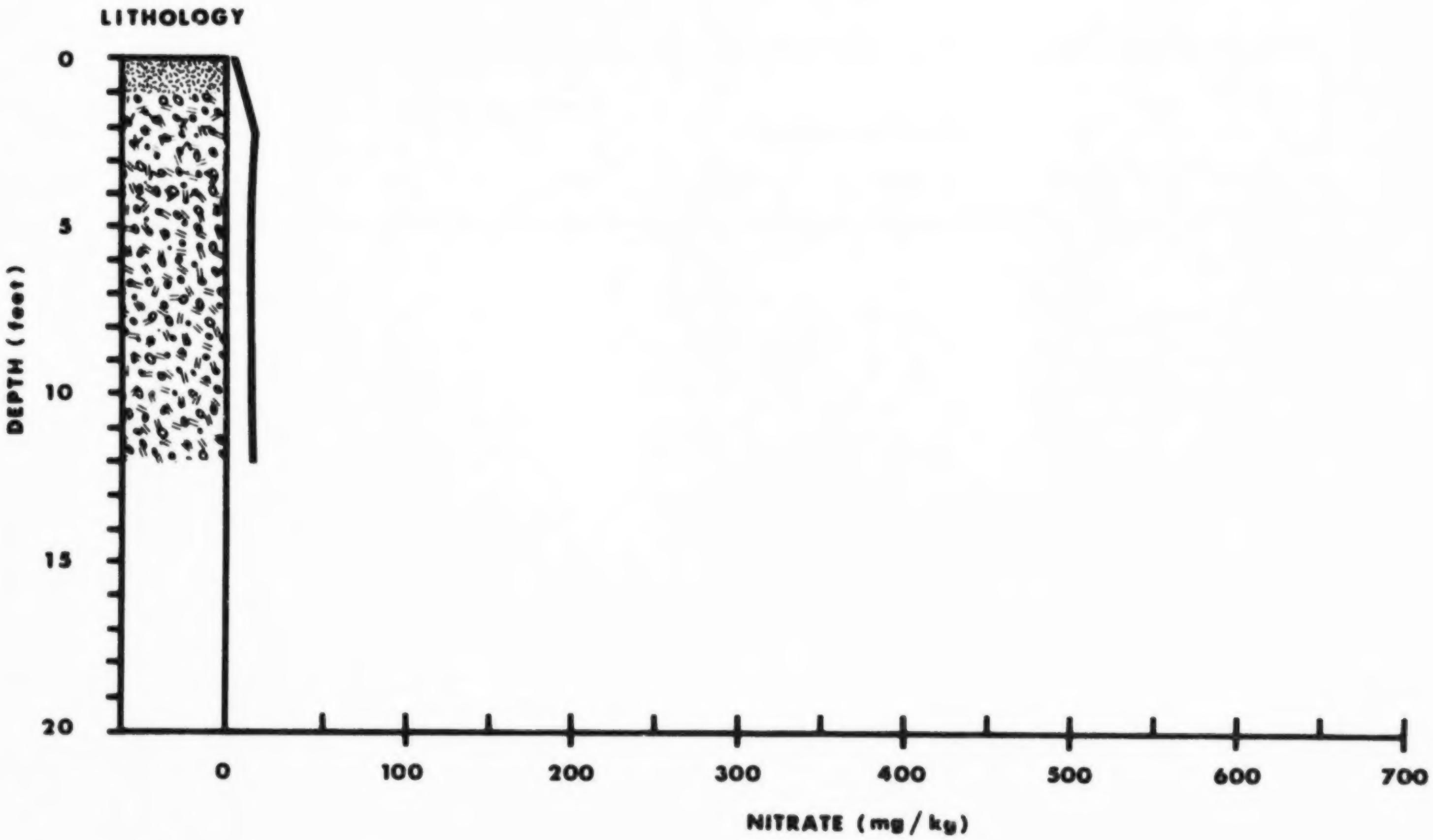
Hole 75. Located 150 feet south of hole 74 in a pasture. 70 #/ acre-foot.



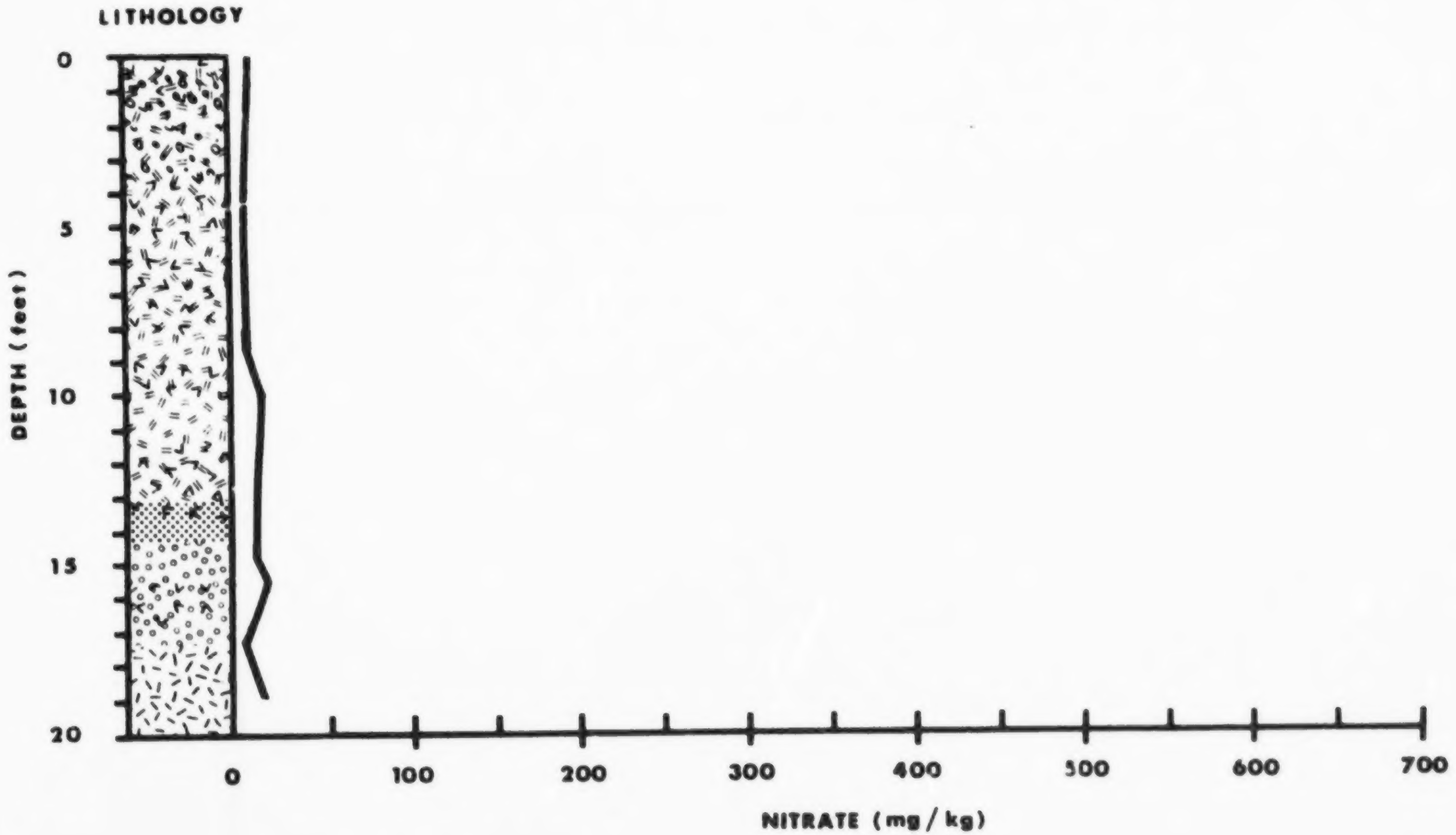
Hole 76. Located 200 feet southwest of hole 74 in a pasture. 66 #/acre-foot.



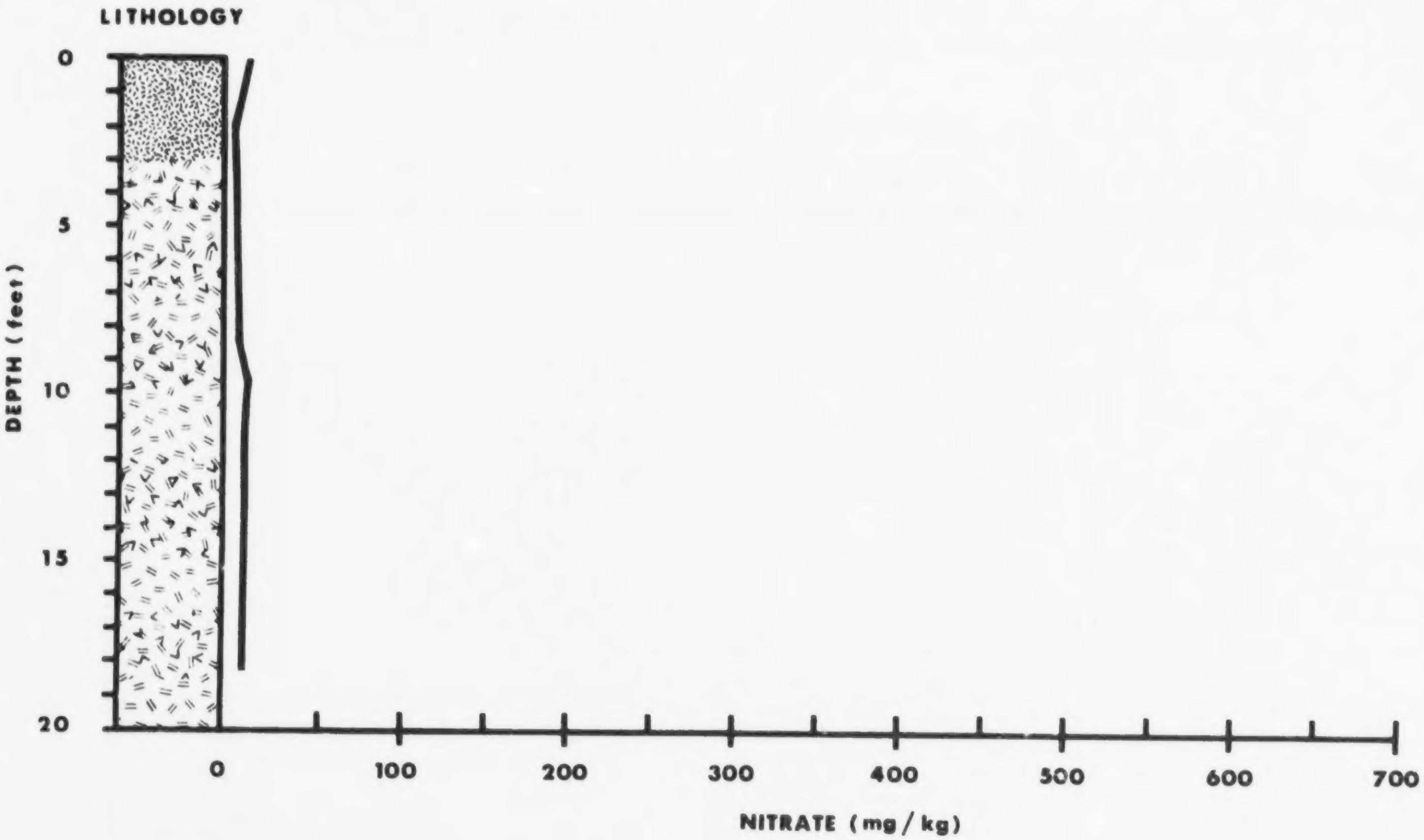
Hole 77. Located 300 feet south of hole 74 in a pasture. 100 #/acre-foot.



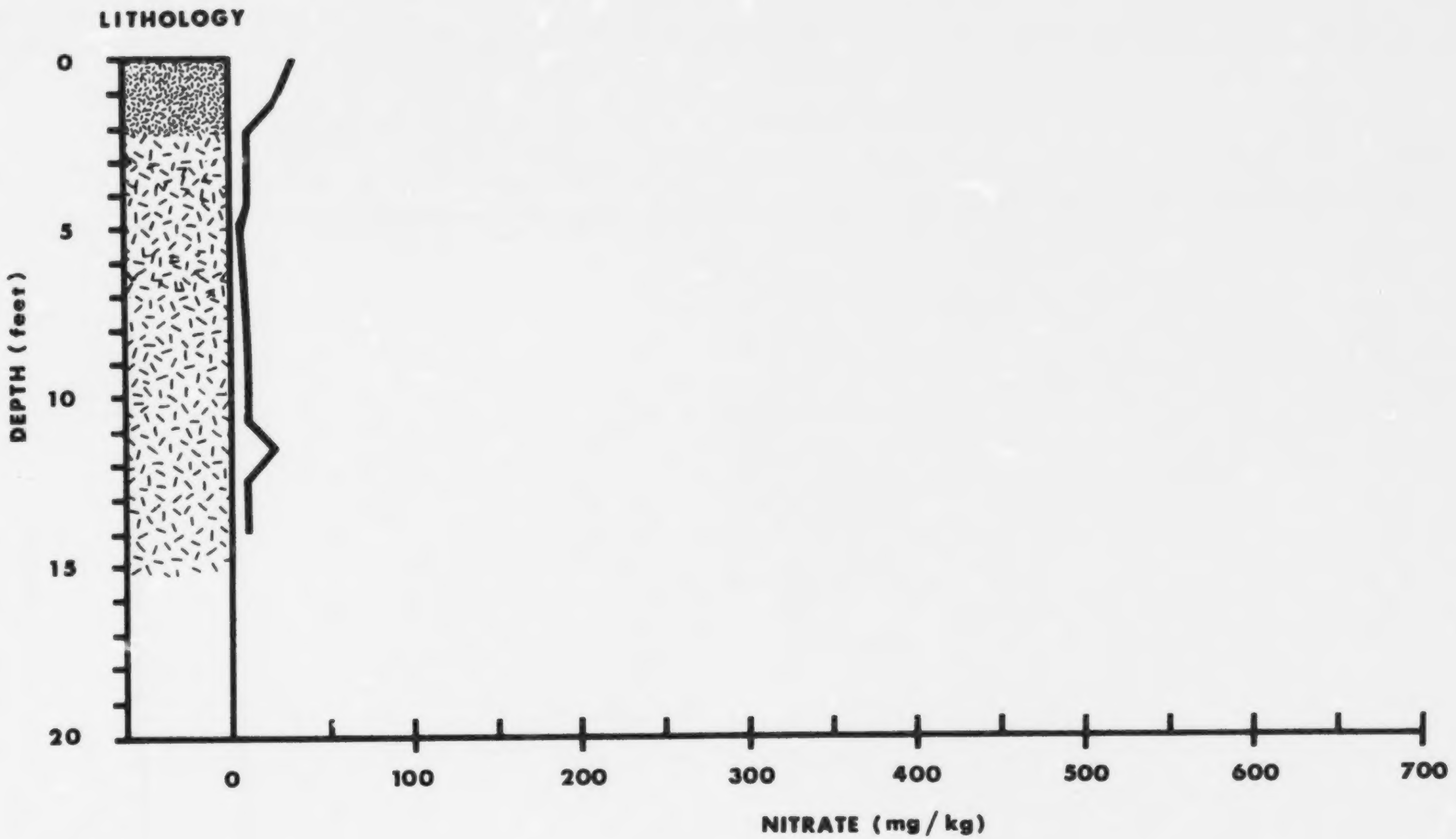
Hole 78. Located 1/4 mile south of hole 74 in a pasture. 82 #/ acre-foot.



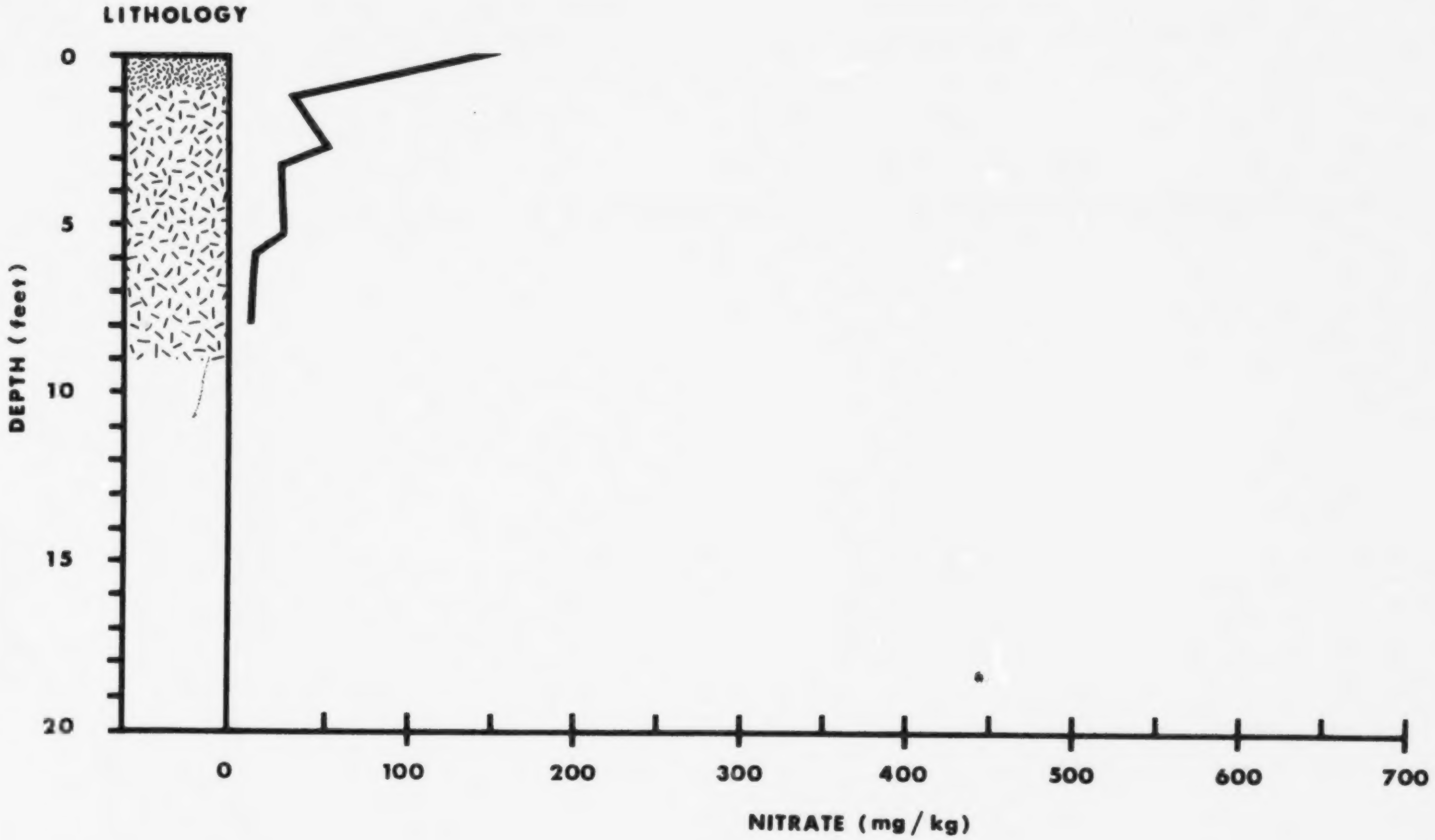
Hole 79. Located 1/3 mile east of well 1115 (130 ppm nitrate) in a mesquite pasture. 75 #/acre-foot.



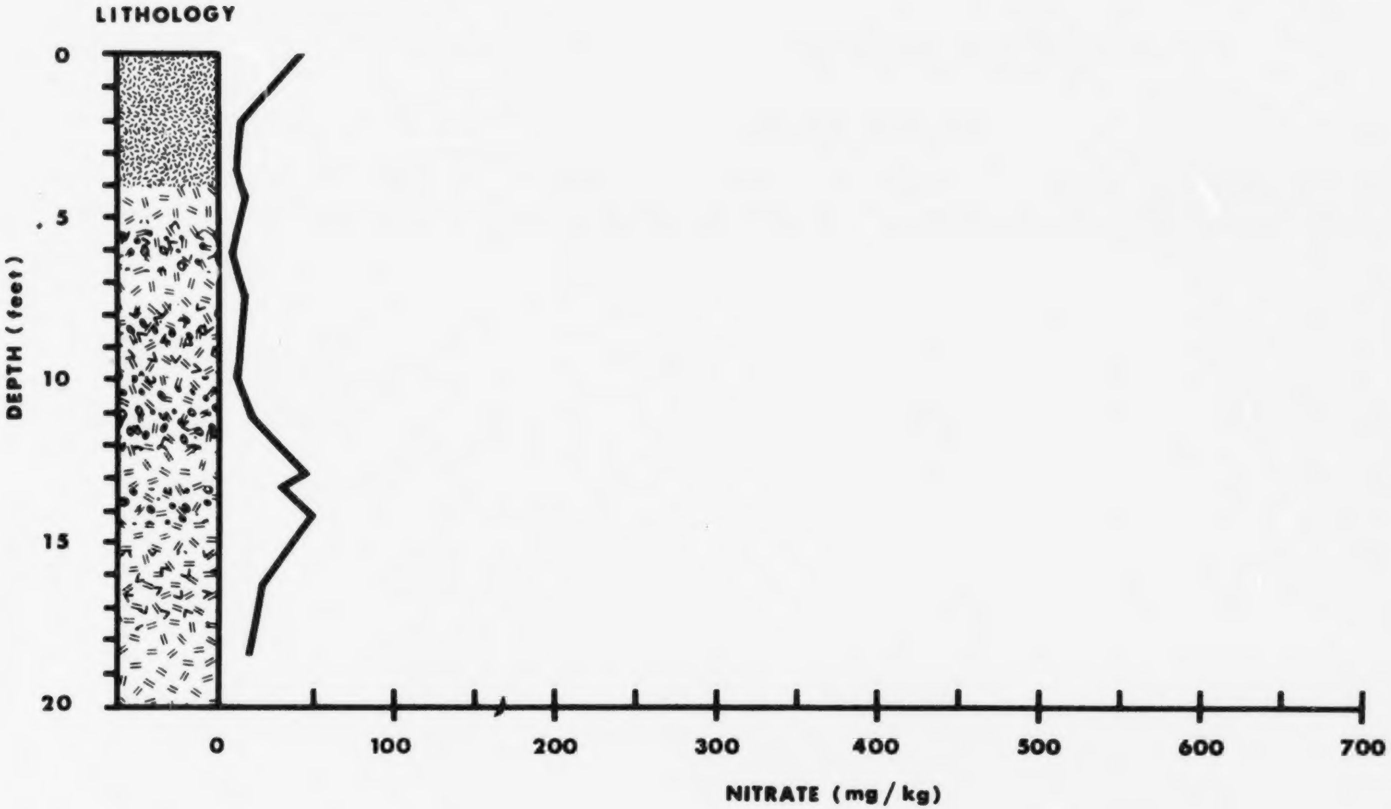
Hole 80. Located 1/5 mile southwest of hole 79 in a pasture.
65 #/acre-foot.



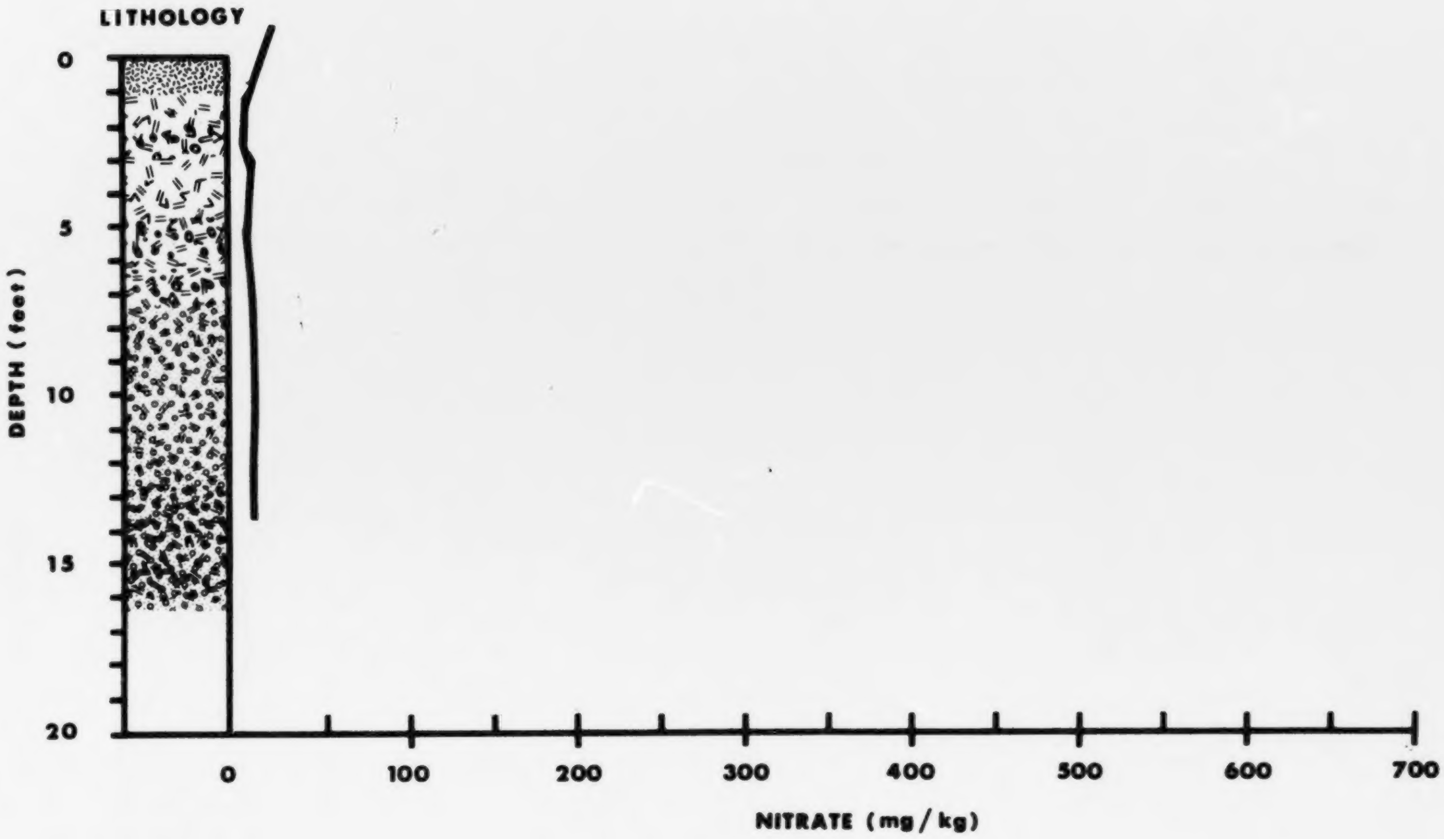
Hole 81. Located 1 mile northwest of well 445 (120 ppm nitrate, 13 feet to water) in a cotton field. 70 #/acre-foot.



Hole 82. Located 400 feet east of hole 81 in a cotton field. 110 #/acre-foot.



Hole 83. Located 400 feet east of well 445 (120 ppm nitrate, 13 feet to water) near an old stock pen which was abandoned 30 years ago. 155 #/acre-foot.



Hole 84. Located 500 feet east of hole 82 in a stock pen. 87 #/acre-foot.